THE ROLE OF POLICY AND MARKETS IN THE DEVELOPMENT OF THE SOLAR PHOTOVOLTAIC INUSTRY: EVIDENCE FROM CHINA

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Public Policy

Georgia Institute of Technology
May 2016

THE ROLE OF POLICY AND MARKETS IN THE DEVELOPMENT OF THE SOLAR PHOTOVOLTAIC INUSTRY: EVIDENCE FROM CHINA

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ACKNOWLEDGEMENTS

I wish to thank my committee members for all the advice that they provided over the entire course of this dissertation. My committee chair and academic advisor for four and a half years, Dr. Marilyn Brown, supported this work from its very inception. She has been a champion for my research interest. She encouraged me to take on opportunities both inside and outside Georgia Tech to advance my research. This work would not be possible without her vision and support.

My three committee members from Georgia Tech, Dr. Jennifer Clark, Dr. Fei-ling Wang, and Dr. Matisoff were all very helpful in making this dissertation stronger. This research is in part inspired by Dr. Clark's dissertation study. Her scholarly work lays the theory foundation of this study. Dr. Wang's International Political Economy class profoundly shapes my view towards the interaction between policy and markets. Dr. Matisoff plays a critical role in ensuring the quality of the quantitative analysis of this study. I am deeply grateful to their teaching.

A special thanks is due to my committee member from Stanford University, Mr. Jeffrey Ball, with whom I spent 13 months, working as part of a team on a research project at Stanford, known as the China Project, that he designed and directed. He trusted me as of one two co-managers of research for the project and let me take the lead in organizing the innovation research and in analyzing the supply-chain related research. His analysis of the Chinese and global solar industry has shaped the structure of this dissertation. His can-do spirit, artful interview skills, and blend of curiosity and critical thinking have greatly influenced me as a researcher and as a person.

Besides my dissertation committee, many institutions and an even greater number of people have lent their generous support to this study.

I want to thank the Stanford Steyer-Taylor Center's China Project for giving me the opportunity to be part of the research, where I got to work with a great team of colleagues. The project, supported by a research grant from the U.S. Department of Energy, offered me a unique opportunity to travel to China three times to participate in the project team's in-depth fieldwork and allowed me to gain access to an ample amount of industry data. These resources advanced my understanding of the solar PV industry in China tremendously. This work is in part inspired by the Stanford project and would not be the same without it. As explained below in Chapter 2 of this dissertation, much of the work in this dissertation is a product of the Stanford China Project and will appear in the Stanford project's report to the public.

In particular, I would like to express my gratitude to the team members of the Stanford China Project. Besides Jeffrey Ball, my direct supervisor and a member of the committee of this dissertation, Dan Reicher, the director of the Steyer-Taylor Center, also offered much useful advice for this study. In addition, he watched out for me at challenging times during international travels. Cait Pollock, the project's other co-manager of research, was supportive throughout the project. A number of Stanford students who participated in the Stanford project as part of a graduate research seminar on the subject also deserve thanks. Yiyi Liu and Di Yao facilitated the data analysis of solar patents. Jingfan Wang and Matt Wells assisted the deconstruction of China's solar-manufacturing supply chain, which laid the foundation for the in-depth investigation conducted in this study. Zhao (Joy) Zhu, during her brief but productive time as a summer research assistant of the Stanford project, analyzed solar-cell efficiency gains in China, which prompted the conclusion that China is in certain areas narrowing the solar-innovation gap with the West. Laurel Mills' analysis of the solar policy landscape in the U.S. provided a useful comparative lens to this research.

I also wish to thank the University of Chicago New Generation China Scholars Program for offering me a scholarship, which made the very first two research trips to China possible. The Program did not only financially support this research, intellectually; it also provided me with two insightful advisors, Dr. Dali Yang and Dr. William Parrish, a community of like-minded young scholars, and a chance to build my initial research network in China. It opened many doors for my later work.

I owe my gratitude to many people and organizations at Georgia Tech for their support and encouragement throughout my graduate school years. The Climate and Energy Policy Laboratory (CEPL) has been my academic home for as long as I have been at Georgia Tech. CEPL witnessed my academic growth and shaped my scholarly identify. I am proud to be affiliated with this productive and impactful group. Members of CEPL, led by Dr. Marilyn Brown, have offered a great deal of helpful feedback to my research. Among all the current and former CEPL student members, Matt Cox has spent the most time brainstorming research ideas with me. With the fortune or the misfortune (I tend to believe it is the former) of being locked in the same office with me for four years, Matt took great interest in my research. He has nurtured, encouraged, challenged, and even fought with me, academically, in his forceful but polite Midwestern manner. I am grateful for the collegiate intellectual relationship with Matt, and with many other CEPL members for that matter. They make me a better scholar.

Besides CEPL, the Ivan Allen College of Liberal Art and the School of Public Policy at Georgia Tech were very generous in offering financial support for my academic adventure, in addition to the high-quality education they provide. The knowledge and skills I learned at the doctoral program have changed my life forever. Furthermore, I am grateful for my Ph.D cohort. Sanjay Aurora, Min Su, Obed Pasha, and Kaspas Berzins are supportive and inspiring friends, who kept me motived.

People whom I interviewed individually and as a member of the Stanford team in China and in the U.S. deserve acknowledgement as well. All of them were very generous in sharing their time, knowledge and opinions. Their openness and deep thoughts are admirable.

There are more people and organizations I want to thank than space allows. I sincerely appreciate everyone who has ever helped, encouraged, challenged and eventually trusted me.

Last but with all my heart, I want to say thank you to my parents for their unconditional love and support. We did not spend a single holiday together in the past eight years due to the fact that there was a whole Atlantic (and then Pacific) Ocean between us. Nevertheless, their faith in me and the value of my work has never changed. They sacrificed a lot to support my academic pursuit. I hope this dissertation will make them proud.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

The development of the solar industry in China has attracted a great deal of attention in recent years with the exponential growth in its solar photovoltaic (PV) manufacturing and installation. Conventional wisdom holds China as a manufacturing giant but a weak innovation player. This study examines the solar PV innovation and manufacturing system in China.

Using solar cell lab efficiency, the quality and quantity of solar PV patents, and publications as three innovation indicators, this study finds that in general, China is closing the innovation gap between itself and the world's leading innovators. Unlike what conventional wisdom assumes, this study shows that the Chinese PV R&D community has been actively engaging in basic science research and has produced noticeable outcomes in certain technology areas, although depending on the choice of innovation indicator, the progress is uneven across the PV technology spectrum.

Three reasons are behind the increasingly active solar innovation in China. Firstly, the Chinese government set a strategic vision for the solar PV industry, which is to achieve both technological advancement and industrialization along the entire solar PV value chain. The vision is then implemented by a suite of science, technology and innovation (STI) programs administered by the Ministry of Science and Technology (MOST) of China. Secondly, the growing public finance support from the central and local governments coupled with corporate R&D investment from major Chinese solar panel manufacturers fuel the innovation in both academia and the industry. Lastly, solar PV R&D in China benefited from an increasingly global innovation network that involves both public and private innovation players from domestic and international institutes. Governments' deliberate effort to recruit overseas well-established scientists and the solar companies' rising attention to innovation both play an important role in forming the network.

In contrast to its increasingly global innovation network, solar PV manufacturing in China thrives on a fully developed domestic supply chain. The supply chain grew out of non-solar-specific suppliers, who co-located and co-developed with the booming solar PV manufacturing industry. The market advantage derived from agglomeration economies combined with government policies that encouraged economies of scale development eventually gave rise to a fully developed, self-sufficient domestic solar PV supply chain that features a few highly concentrated industrial clusters, such as the one in the Yangtze River Delta area.

This study discovers that a fully developed domestic supply chain could offer multiple benefits to domestic industries. It provides them with cheaper alternative tooling and material options that directly reduce their production costs. It lowers the transaction cost associated with communication between suppliers and producers and enables collaborative local learning. In addition, the agglomeration economies created by the domestic supply chain lock the cost and logistic advantage within the country and gives it unique infrastructure, business, and knowledge advantages that are difficult to duplicate elsewhere.

Despite the importance of a domestic supply chain, the quantitative and qualitative analyses conducted by this study finds that it is impossible to point to one factor as *the* root of competitiveness. Rather, this study identifies 15 factors that cover five realms of potential sources of competitiveness: agglomeration economies, firm strategy, culture, resource, and policy.

Nevertheless, the Chinese solar PV industry still faces a few stubborn weaknesses. MOST's utilization of the STI programs was inefficient and ineffective due to its lack of policy consistency and continuity, its own less-than-perfect technology forecast, and inaccurate market feasibility assessment. Local institutions, including local governments and universities, have not developed the tenacity to building innovation strength, and the weak innovation capacity jeopardizes the competitiveness of the manufacturing sector and the development of the supply chain, making it difficult for them to gain strength in areas that require advanced knowledge and manufacturing skills. Besides, the industry-wise pursuit for quick commercial success via the low road development strategy caused a range of problems, from low product quality to poor product performance. As consumes become more and more sensitive to efficiency and reliability of their solar PV systems, the low-cost strategy is likely to cause problems for the Chinese PV industry in the future. Last but not least, an overshoot of the economies of scale strategy fueled by easy access to capital and local governments' short-term-interest-driven economic development decisions led to rapid but irrational expansions of manufacturing capacity.

A few policy lessons can be learned from the study of the solar PV industry in China. First, setting a national vision and then following it up with concrete strategies can energize an industry. Second, a country's manufacturing capacity is as strong as its innovation strength. Therefore, countries should use innovation as a crosscutting lever to integrate R&D conducted in labs with manufacturing innovation and supply chain innovation. Innovation policy, industry policy, and market-adoption policy should be designed in synergy. In addition, policies should also be crafted to match to the right geographical scale. In particular, policies that promote the development and diffusion of codified knowledge should aim for a global reach whereas local industrial clusters and networks are preferable when the focus is on retaining and diffusing tacit knowledge.

CHAPTER 1

INTRODUCTION

1.1. Background

In the wake of rising energy demand, a changing climate and deteriorating environmental quality, many countries have made developing renewable energy resources one of their top priorities. Among all types of renewable energy, the development of the solar energy industry has attracted a great deal of attention in recent years with its exponential growth in global solar photovoltaic (PV) installed capacity. China stands out in this ongoing solar revolution. Chinese solar PV installed capacity has doubled every year since the passage of Renewable Energy Law in 2006, reaching 7 GW total installed capacity in 2012 (Montgomery, 2013). In 2013, China installed close to 12 GW of PV capacity (BNEF 2014a), surpassing Germany and the United States for the first time to become the world's largest PV installer. The figure was slightly lower in 2014, which was 10.6 GW, but it pushes the total installed solar capacity of the country to 30 GW (National Energy Administration, 2015). It is reported that in the first nine months in 2015, China added another 9.9 GW solar capacity to its fleet (Xinhua News Agency, 2015c). The National Energy Administration, China's energy regulative body, announced in October 2015 that China had set an installed capacity goal of 150 GW solar for 2020 (Xinhua News Agency, 2015b).

Behind the country's fast deployment of solar PV is China's world's largest PV manufacturing industry, which has grown from almost non-existent in early 2000s to account for 70% of the global solar PV production in 2014 (GTM Research, 2013). Today, China has at least 65GW of solar module production capacity (PV-Tech, 2014). Seven out of the ten World's largest PV manufacturers in 2014 are Chinese (PV-Tech, 2014).

China's ability to quickly develop a new energy industry has caught the world's attention, but it also puts its entire PV sector under scrutiny. First, its pursuit of a "low road" (cost driven) strategy instead of a "high road" strategy (high productivity) has trapped the industry in the lower value-added segment of the global market. Although solar PV modules made in China were sold worldwide, not many of them have state-of-the-art electric conversion efficiency, a key indicator that measures the performance of solar PV. In fact, China is a latecomer to PV technology innovation. The U.S. National Renewable Energy Laboratory (NREL) tracks the world record lab efficiency of 23 types of PV technologies between 1975 and 2014 and none of them was set by Chinese entities. Even in the commercial production realm, Chinese companies are often known as producers of low- to medium-efficiency but affordable solar PV. In today's market where the cost of solar panels has declined so significantly that room for further cost reduction is limited. The manufacturing industry and the research community in China are in fact eagerly yearning for innovation because they have exhausted almost all the potentials of the low road strategy. Second, the way that Chinese PV manufacturers achieve its global market dominance is challenged by American and European solar PV manufacturers. They alleged that the reasons Chinese PV manufacturers were able to achieve cost competiveness were because they received "illegal" subsidies from the government and they sold their products at prices below their production costs. The claim led to bitter trade fights between China and E.U. and the U.S. over China's solar panel exports.

The securities challenge the entire legitimacy of the solar PV sector in China, from research to manufacturing. Essentially, the critics construct an alternative view that there is no real solar PV technological innovation in China; and the reason that the Chinese solar PV industry is competitive is because of government subsidized low-cost production.

Challenges from the critics in fact pointed to some quintessential questions that any emerging energy technology, or any new socially and environmentally friendly technology in general for that matter, has to answer, which are how to develop the innovation capacity around a new technology? And how to effectively and efficiently scale up the manufacturing in order to facilitate its market creation and to advance its adoption in the market? This study intends to contribute to the search for answers to these questions by using the solar PV industry in China as an example.

1.2. Research Objectives

This objective of the dissertation is threefold. First, it intends to explain the development of the solar PV industry in China using the Technological Innovation Systems (TIS) framework and explain the mechanisms that lead to the successes and failures in the industry. This study defines the "development" of the solar PV industry as containing three dimensions: the advancement of solar PV research; the creation and sustaining of PV manufacturing competitiveness; and the scaling up of the solar PV supply chain. By analyzing the structure and functions of the industry and the mechanisms through which drivers and barriers are created that either facilitate or block the development of the industry, this dissertation proposes to answer the following questions:

Where does China stand in terms of solar PV innovation relative to the world's leading innovators? And what policies and market dynamics enabled or impeded the advancement of solar PV innovation?

What are the sources of market competitiveness among Chinese PV manufacturers? And how can they be translated to other socially and environmentally friendly technology-related manufacturing industries?

What market and polices forces led to the development a regionally clustered solar PV supply chain in China despite the strong force of globalization? And how did it contribute to solar PV innovation and manufacturing?

What lessons can policymakers draw from China's experience to design better policies to facilitate the development of future new socially and environmentally friendly technology-oriented industry?

At the center of the quest to answer these questions lies the effort to understand the interactions between public policy and markets. Comparing to conventional energy industries like the petroleum and coal, the solar energy industry is still at its initial stage of development; policies can have significant impacts on the growth trajectory of the industry through providing incentives, setting standards, or rewarding certain behaviors (Lewis & Wiser, 2007; Mitchell, 2010). Therefore, this dissertation will examine the development path of the Chinese PV industry from the policy perspective by applying the TIS framework to examine the functions and impact of various policies (known as ***institutions*** in TIS terms)[1], and explain the dynamics between the policy tools, market forces, and market behavior of industry players in order to identify the drivers and barriers and illustrate the processes through which they induce or block the development of the industry.

This work will draw insight from the national technological innovation systems (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; B Å Lundvall, 2010; Richard R. Nelson, 1993), economic geography (S Christopherson & Clark, 2009; Clark, 2013; Dicken, 2011; Gordon & McCann, 2000), industrial policy (K. S. Gallagher, 2014; Lewis, 2013; Nahm & Steinfeld, 2014a), political economy (Mitchell, 2010; Zhao, Zhang, Hubbard, & Yao, 2013a), and energy policy (M A Brown & Sovacool, 2011; Sovacool & Brown, 2015) literature. By examining the innovation system and the manufacturing system first independently and then synergistically using first-hand empirical evidence, this work hopes to explore the links across different policy areas in

1 Terms and phrases special to the TIS framework will be put in bold and italic font throughout the dissertation.

order to shed practical light on policymaking that aims to effectively and efficiently development a new socially and environmentally friendly technology-based industry.

In addition, this dissertation means to develop methods that can quantitatively test the causal factors of market competitiveness among leading Chinese solar PV manufacturing firms. Much of the ongoing trade dispute between the U.S. and China stems from the different understanding of the source of cost-competitiveness at the firm level (Goodrich, Powell, James, Woodhouse, & Buonassisi, 2013a; U.S. DOC, 2012a, 2012b). Building on literature about technology innovation (Breznitz and Murphree 2011; de la Tour, Glachant, and Ménière 2011; Lewis 2013; Mohr 1969; Nelson 1993a), competitive advantage in manufacturing (Fujita & Thisse, 2013; P. Krugman, 1991a; Nahm & Steinfeld, 2014a; Teece, 1980; Weiss & Bonvillian, 2009) and industrial policy (Clark, 2013; Milstein Commission on new Manufacturing, 2014; Rodrik, 2004), this work aims explore the production cost of tier-1 solar PV manufacturing firms using firm-level data in order to understand low cost production among Chinese firms in relationship to potential causal factors like subsidies, economies of scale, and innovation. Fuzzy set-Qualitative Comparative Analysis (fs/QCA) approach will be used to as the main quantitative tool to accomplish this task. This analysis will offer empirical evidence to inform the debate about the true sources of market competitiveness in the solar manufacturing area. More importantly, it will advance the academic discourse on building and maintaining economic competitive advantages of a firm, and shed light on policy design that aims to facilitate the building and scaling up of a new socially and environmentally friendly technology-based industry.

1.3. Structure of the Dissertation

The remaining chapters of this study are organized as follow. Chapter 2 will introduce the TIS framework, the quantitative and qualitative research methodology and data. Chapter 3 dives into the innovation subsystem to examine whether it has been effective in producing innovation progress and what mechanisms lead to the progress or the lack thereof. Chapter 4 provides analysis of the development of the manufacturing subsystem and its sources of competitiveness using both quantitative and qualitative methods. Discovered that the supply chain development is the most prominent feature of the manufacturing subsystem, Chapter 5 has an in-depth look at the supply chain, its history, characteristic, and most importantly the role it plays to link the innovation subsystem with the manufacturing subsystem. Finally, Chapter 6 will bring the findings together and explore the inherent connections between innovation, manufacturing, supply chain development, and deployment. Although PV deployment will not be discussed in its own chapter, its interactions with the manufacturing sector will be explored.

CHAPTER 2

METHODOLOGY AND FRAMEWORK

2.1. Introduction

A mixed-method approach will be used to qualitatively understand the processes through which policies and markets interact and influence the development of the PV industry as well as quantitatively assess the competitive advantages that PV manufacturing firms developed in response to different policy and market environment. The qualitative analysis will be guided by the Technological Innovation Systems (TIS) framework. The structural components of the solar PV TIS, such as the actors, their networks and the institutions that govern them will be analyzed. TIS also emphasizes qualitatively assessing the processes through which driving- and blocking-mechanisms are formed and used to either advance or impede the development of the solar PV TIS. More than 120 semi-structured interviews with solar PV professionals, researchers, analysts and policymakers have been conducted. Content obtained from these interviews will be used as data for qualitative analysis under the TIS framework. In addition, the causal factors that lead to lower solar PV production cost among Chinese solar PV manufacturers will also be quantitatively examined.

Much of the research, analysis, and writing that undergirds this dissertation was done as part of the China Project at Stanford University's Steyer-Taylor Center for Energy Policy and Finance. That project, as of the submission of this dissertation, was in the process of finalizing a comprehensive report that will be published widely. The Stanford report chronicles and analyzes changes in China's dominant role in the global solar industry; examines in particular developments in China's innovative capacity in solar and in its solar supply chain and the drivers and implications of those innovation and supply-chain advances; assesses what the changes in the Chinese solar industry say about the comparative advantages of China and of other countries, including the United

States, in the globalizing solar industry; and, in light of that analysis, recommends policies that different countries might pursue to play to their comparative advantages in a way that minimizes the cost of scaling up solar power for the world. Much of the work that appears in this dissertation, which the Stanford Project has by courtesy allowed to be presented in this dissertation, was done in concert with multiple members of the project's Stanford research team and will appear in the Stanford project's report. In particular, the data and analysis prompting the conclusion that China is in certain areas narrowing the solar-innovation gap with the West, the data and analysis deconstructing China's solar-manufacturing supply chain, and interviews with dozens of solar executives, policymakers, and academics in China are key parts of the Stanford project's work. As explained above in the Acknowledgement section, the author of this dissertation took the lead while at Stanford in organizing the innovation research and in analyzing the supply-chain related research.

2.2. Qualitative Analysis: Framework and Its Application

2.2.1. Technological Innovation Systems as an Analytical Framework

This dissertation will use Technological Innovation Systems (TIS) as the main theoretical framework to conduct qualitative analysis. TIS examines a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure to pursue the development, diffusion, and utilization of one technology (Bergek et.al., 2008).

Figure 2.1 illustrates the analytical flow of the TIS framework. It begins with identifying the technological innovation system in focus and the actors, networks, and institutions involved in the system. One highlight of the TIS framework is that it pays special attention to the processes that affect the overall wellbeing of the system (Hekkert et.al., 2007; Jacobsson and Johnson, 2000). It does so by first identifying key ***functions*** of the system, i.e. the contributions of one component or a set of components to the advancement of the system. Seven functions are at the heart of the TIS framework: knowledge development, resource mobilization, market formation, influence on the direction of search, legitimation, entrepreneurial experimentation, and development of positive externalities. The next step is to assess how the processes of fulfilling these functions work in a TIS. When examining the processes, the TIS framework evaluates how well these processes work to advance the functions of the system and identify the mechanisms that either drive (induce) or block the development of the functions, which in turn impact the overall wellbeing of the TIS. The driving (inducement) and blocking mechanisms are the key products of a TIS analysis because they explain the success and failure of a technological innovation system in creating and developing its functions. They also explain how each function individually and/or collectively serve to improve or hinder the wellbeing of the overall system. Policy recommendations can be offered based on TIS analysis to promote the identified good practices and tackle the barriers created by blocking mechanisms.

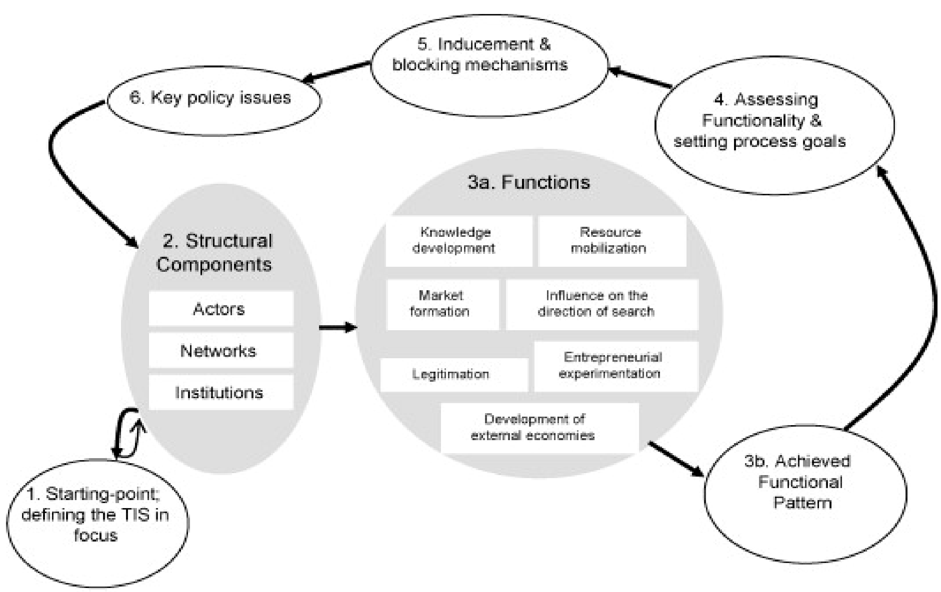

Figure 2.1 Analytical Flow of Technological Innovation Systems Framework
Source: Bergek et al. 2008

2.2.2. Key concepts in the framework

Technological Innovation System: a dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the development, diffusion, and utilization of technology.

Structural components of a TIS: a group of components serving a common purpose, which is to uphold the goals of a TIS.

Actors: players who are involved in the development, diffusion, and utilization of a certain technology.

Networks: an intermediate form of organization between actors. Their essential function is to facilitate information and knowledge exchange.

Institutions: formal institutions refer to rules, laws, regulations, and policies. Informal institutions include culture and social norms.

Functions: the contribution of a component or a set of components to the overall wellbeing of an innovation system. They are the processes that directly influence the development, deployment of a new technology and consequently affect the performance of the innovation system. The TIS framework focuses on understanding the process of technology innovation through assessing seven functions of an innovation system.

Knowledge development and diffusion: the expansion of a TIS's knowledge base by adding new knowledge and new sources of knowledge. It also concerns with the evolution of the knowledge base over time via learning and knowledge diffusion.

Influence on the direction of search: activities that shape actors' needs, requirements and expectations with respect to their involvement in developing and advancing the emerging technology. It is a combined strength of incentives, pressures, or even coercion (Bergek et al., 2008).

Entrepreneurial experimentation: the risk-taking behaviors with regard to the uncertainties of new technologies and markets that eventually reduce the uncertainties for latecomers. It opens up the door for new technologies to make inroads into the mainstream market.

Market formation: the multi-phased process to create, nurture, and solidify the market presence of technologies at concern.

Legitimation: the act to gain the social acceptance, align with the incumbent institutions, or establish new rules of the game. It is the prerequisite for a new industry to become a mature industry. Ways through which legitimation can be created include: institution alignment; manipulation of rules of the game; conformance with the existing rules; and creation of new rules of the game.

Resource mobilization: the ability of an actor or a technology to draw on resources such as financial assets, human capital, social support, regulatory endorsement and etc. to one's own benefit.

Development of positive externalities: a positive feedback loop that allows one function to help the fulfillment of other functions. For example, the market creation function fulfilled by the PV manufacturing subsystem facilitates the legitimation of the subsystem.

Mechanisms: "the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes." (Myrdal, 1957). TIS aims to understand two types of mechanisms: the driving mechanism and the blocking mechanism. A driving mechanism provides inducing force to a TIS to facilitate the fulfilling of certain function(s) and improve the overall wellbeing of the TIS. A blocking mechanism is a negative force that impedes a TIS' efforts to develop its function(s) and hurt the overall wellbeing of the TIS.

2.2.3. Apply TIS to the Solar PV Industry in China

The scope of the system includes three distinct but interrelated subsystems: the PV technology innovation subsystem, the PV manufacturing subsystem, and the PV deployment subsystem (Figure 2.2). The reason to divide the solar PV TIS into three subsystems is partly because different skills and products are involved in different subsystems. More importantly, from the policy and political economy perspective, each subsystem is governed by a distinct set of institutions: the PV innovation subsystem is heavily influenced by the national innovation system in China and the specific science and technology policies that it promulgates.

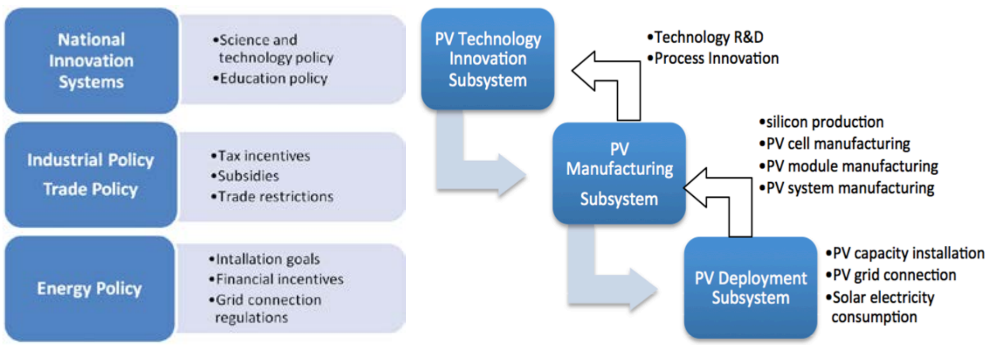

Figure 2.2 The Scope of Solar PV Technological Innovation Systems

In a broader sense, the PV technology innovation subsystem is essentially part of the large network that connects the government policies with education system, enterprises, and a suite of enabling infrastructures such as the financial market and the labor market and so on (B Å Lundvall, 2010; Richard R Nelson, 1993). In a narrower sense, the subsystem is under the direct influence of the country's and companies' R&D budget and its non-financial capacity to innovate such as its research talents and its attention to manufacturing processes. From a public policy perspective, policies that are most relevant to this subsystem is administered by the Ministry of Science and Technology (MOST) in China (de la Tour et al., 2011; Lewis, 2013; Sun, 2013). MOST is in charge of setting agendas for PV technology innovation. Besides agenda setting, these agencies also carry out another important function –allocating R&D funding among various players. Chapter 3: The Solar PV Innovation Technological Innovation Subsystem in China examines the development of the subsystem in details.

Unlike the innovation subsystem, the manufacturing subsystem is in essence an industrial sector. In the Chinese context, it is regulated by industrial policies promulgated by NDRC, China's top economic decision-making agency, and Ministry of Industry and Information Technology (MOIIT) (Andrews-Speed, 2012; Breznitz & Murphree, 2011). Policies used to facilitate the development of the PV manufacturing industry include a combination of tax incentives and subsidies on labor, capital and material inputs. Market plays an important role in shaping the development path of the PV manufacturing firms in China. In addition, trade policy plays an increasingly important role in shaping the manufacturing landscape as globalization continues to change the way goods are produced. The recent trade conflicts that China had with the U.S. and the E.U. are examples of the impacts of trade policies. Chapter 4: The Solar PV Manufacturing Technological Innovation Subsystem in China is dedicated to study the PV manufacturing subsystem.

Supply chain stands out as a unique and consequential feature of the solar PV manufacturing subsystem in China. Its sheer size, degree of sophistication, and continuous evolvement make it a one-of-a-kind factor that differentiates the PV industry in China from the rest of the world. Yet, there has not been a single study that dives into the history and nuances of the solar PV supply chain in China. Moreover, the how the supply chain has enable the development and the maturation of the PV industry has not been thoroughly investigated. Chapter 5: Supply Chain of the Solar PV Manufacturing Industry fills this blank by detailing the history and current state of solar PV supply chain in China, and the mechanisms through which it facilitates the growth the overall PV manufacturing industry.

Although the PV deployment subsystem is considered as part of the national energy infrastructure system, this dissertation does not include the PV deployment subsystem in the scope. Part of the reason is that the deployment system has very little connection with the innovation subsystem, albeit it is intertwined with the manufacturing subsystem. The latter relationship will be explored in Chapter 4: The Solar PV Manufacturing Technological Innovation Subsystem in China.

2.3. Qualitative Analysis: Data and Research Design

Under the TIS framework, this dissertation will use qualitative semi-structured interview data and documents on government directives, policies, ordinance, and political debates to examine the functions and mechanism developed in the three subsystems, and how they contribute to the wellbeing of the solar PV industry.

2.3.1. Qualitative Data

Interview data were collected during five research field trips to China between December 2013 to June 2015. Given the similar research structure between the Stanford China project and this dissertation, this dissertation has the fortune to draw from rich interview data collected by the Stanford China Project. In the last three research trips, the author of this dissertation traveled and worked with at least one, and sometimes two, other members of the Stanford project's research team. During the trips, the author attended two academic conferences and two trade shows, and, usually as a member of the Stanford research team, participated in 124 semi-structured interviews, and took 28 site visits to 16 silicon, solar cell, solar module, and manufacturing tooling production plants and nine site visits to PV research labs, two visits to industrial parks, and three site visits to distributed solar PV deployment sites. In addition, the researcher worked with other members of the Stanford project to organize three workshops on the topic of the Stanford project and to present the Stanford project's research preliminary findings for feedback. Two of those workshops were held at a Stanford University facility in Beijing, China, and one was held at the Brookings Institution in Washington, DC. Table 2.1 summarizes the data-collection activities in China.

The selection of the interviewees and site visits means to cover the three subsystems of the solar PV industry by including as many major stakeholders from each subsystem as possible. The final distributions of interviews and site visits reflect this design. The manufacturing subsystem has the largest number of interviewees: 46 people gave 49 interviews, and majority of the interviewees are senior managers and executive officers at leading China PV manufacturers, such as Trina, Yingli, Canadian Solar and more. The solar PV innovation subsystem has the second largest number of interviews (not counting the Policy-making/Consulting/ Industry Association category, which is a cross-cutting category that touches on all three subsystems). 27 interviews were conducted with 22 science and technology experts. They come from two sectors: academic institutes, and R&D divisions of large Chinese solar corporates. The PV deployment subsystem has the least number of interviewees; 15 people working in the PV project development sector were interviewed. Interviews conducted with policymakers at the central and local levels also provided good amount of insight into the deployment sector. These interviewees are categorized under the Policy-making/Consulting/ Industry Association category; along with solar-focused consultants from global leading firms such as Bloomberg New Energy Finance, IHS, and etc., and professional from solar and renewable energy associations in China, they offered a balance to the number of opinions collected across the three subsystems. Table 2.1 in Appendix A includes high-level information about interviewees.

Table 2.1 Summary of Data Collection Activities in China

Sector	Number of Interviews	Number of People Interviewed
Solar PV Innovation	27	22
Solar PV Manufacturing	49	46
Solar PV Deployment	17	15
Policy-making/Consulting/ Industry Association	31	26
Total number of semi-structured interviews	124	108
Site Visits		
Type of Site	Number of Visits	
Solar PV Cell/Module Manufacturing facility	13	
Solar PV Materials and Tooling Manufacturing facility	3	
Solar PV Research Laboratory	9	

Table 2.1 Continued

Type of Site	Number of Visits
Solar Deployment Site	3
Industrial Park	2
Total number of site visits	28
City Visits	
Total number of Chinese city visits	10 cities over 5 trips to China Tianjin, Beijing, Shanghai, Suzhou, Baoding, Changzhou, Hangzhou, Jiaxing, Nanjing, Changsha
Trade Shows and Academic Conferences	
Trade Shows and Academic Conferences attended	4
Workshops	
Workshop helped organized and presented at	2 in Beijing, China 1 in Washington D.C., U.S.

In addition to interviews, the author, usually as part of the Stanford research team, also participated in 28 site visits in 10 Chinese cities, including 13 different solar cell and module manufacturing facilities, and three factories of solar PV materials and tooling suppliers (one poly-silicon supplier, one glass supplier, and one tooling supplier), nine academic and corporate research labs, three distributed solar PV project sites, and two clean energy and advanced manufacturing-oriented industrial parks. These site visits are valuable because they offer inside looks to the state of the three subsystems in China. From the combination of the site visits and semi-structured interviews, the author was able to have a first-hand understanding about the organization and operation of Chinese manufacturing firms, the types of machinery they use, the level of automation, and their corporate culture; the research condition of Chinese labs, the types of equipment and research approach they use in their experiments; as well as the process of building a rooftop solar PV projects. Table A.2 in Appendix A provides more information about these site visits.

2.3.2. Qualitative Research Design

In general, the design principle of the semi-structured interviews adheres to the TIS framework in a sense that it tries to identify both the structural components of the PV TIS, i.e. the players, networks, and institutions. The questions intend to tease out the functions fulfilled by each structural component, and more importantly the drivers and barriers that either spurred or prohibited the development of the industry or a particular firm.

In addition to first hand interview data, written records on governments and firms decision-making process are also valuable qualitative data. They reveal the motives of governments and firms' actions as well as the incentives that drive them and the obstacles that prevent to make certain decisions and the compromises they make in between. Sometimes, when used independently, semi-structured interviews and official written documents could represent certain rhetoric that reflects the preferred image that particular players want to be seen as to the outside world. Therefore, it is important to use both types of qualitative data in combination in order to tease out the real motives and actual inner working of a decision-making body such as a government agency or a firm.

2.4. Quantitative Analysis: Data and Research Design

To assess the state of solar innovation system, this study tracks three types of innovation performance indicators: public and private R&D, solar cell-efficiency record in China, and solar PV-related patents data in Chin and in the U.S.

In order to understand the source of cost-competitiveness, this study will unpack the cost of producing solar PV in leading Chinese firms using fussy set Qualitative Comparative Analysis (fs/QCA). Fs/QCA is a comparative approach that is fit to analyze the causal configurations of a set of variables that consistently appears or does not appear in order to produce certain outcome. It is based on the idea that causal relations are frequently better understood in terms of set-theoretic relations rather than correlations

(Ragin, 2000, 2008, Fiss, 2007; Ragin, 1987, 2000, 2008; Ragin & Fiss, 2008). It uses Boolean algebra to create algorithm to reduce numerous causal possibilities to a set of configurations that lead to outcome (Fiss, 2011). Fs/QCA does not rely on large sample size to draw statically inference, which is suitable for this study.

2.4.1. Quantitative Data and Research Design Related to Solar PV Innovation

This study collected quantitative data related to three innovation performance indicators: R&D spending, solar cell efficiency and solar PV patents.

Data collection related to public R&D spending was met with great difficulties, due to the poor information collection and management system in China and its lack of transparency. Section 3.4.1.2 in Chapter 3 will have a longer discussion on this point. Despite of the challenge, this study explored almost all the means possible to collect the R&D investment data since the 10^{th} FYP. Methods for data collection include searching public databases, tracing government documents, and interviewing people who involved in R&D funding decision-making. Results can be found in Chapter 3 Sector 4.1.

To measure the progress made in the innovation system, this study take the five solar cell technologies from three-generations of solar PV, track the record cell efficiency in Chinese and compares it to the evolution of the world record cell efficiency. The effectiveness of the innovation system in China is measured using the change of the gap between the two. In all five technologies, record efficiencies were lower in China at the beginning. If over time, the gap between China and the world's leading level narrows, it suggests that the China's solar innovation strength has grown and vice versa. Data on solar cell record efficiency in China was collected from a thorough literature and technical document review as we as interviews of technology experts. Data on the world solar cell record efficiency was collected based on data from the U.S. National Renewable Energy Laboratory (NREL, 2014). Chapter 3 Sector 4.1 will discuss the findings.

Solar PV patent data are from two sources: China's State Intellectual Property Office (SIPO) and U.S. Patents and Trademarks Office (PTO). With assistance from a China-based patent analytical firm Evalueserve[2], which donated its time and insight as part of the Stanford project, patent-search strategies were developed for all 16 types of solar PV technologies that are currently active in either the commercial or research area. The search strategies were then applied to the SIPO database to extract patents related to the PV technology scientific research, excluding those associated with PV manufacturing and deployment, just to tease out the real impact of hardcore scientific innovation in the solar PV arena. A similar approach was then applied to U.S. PTO database. Patent quantity, measured in number of patents granted to Chinese entities over time in both the Chinese and U.S. market, and patent quality, measured in patent lapse rate were used as two indicators to measure the effectiveness of the solar PV innovation system in China. Findings will be discussed in Chapter 3 Sector 4.2.

2.4.2. Quantitative Data and Research Design Related to Solar PV Manufacturing

Data used in this study to unpack the manufacturing competitiveness come from Bloomberg Industries (BI)'s solar industry database, known as BI SOLAR (Bloomberg Finance L.P., 2014a). BI SOLAR contains information related to the entire value chain of the global solar energy industry, from silicon manufacturing, to PV cell and module production, and eventually the installation of and electricity generation from solar panels.

BI SOLAR divides industry players into different peer groups, each consisting of players that meet a certain set of standards. The Global Large Solar Energy Valuation Peers (LSEP), also known as Tier 1, includes 15 global leading solar energy firms, among which 13 are solar PV module producers, 1 is wafer producer (SunEdison), and another one 1 silicon producer (GCL-Poly). For the purpose of this study, the sample is

[2] The author was one of two co-managers of research Stanford University's China Project at the time when Evalueserve (http://www.evalueserve.com) volunteered its patent-data-analysis services to the Stanford research project.

limited to PV module producers only. Among the 13 PV module producers, 11 of them report information on production cost, manufacturing capacity and production, which are three crucial variables to this study. 9 of them are Chinese firms. Table 2.2 summarizes the key statistics of the 9 PV module manufacturing firms that comprise the sample of this study. Together, they accounted for at least 40.3% of the global PV module production in 2014. This study uses firm-level quarterly data because they provide good granularity on Chinese firms' financial and manufacturing information. More information about the data and sample set will be introduced in Chapter 4 Section 4.2.2. Quantitative Research Design and Data.

Table 2.2 PV Manufacturing Companies Considered in This Study

Company Name	Country of Production	2011 Production as % of world total	Year Went Public	Stock Trading Venue	Founder
Trina Solar	China	7.60%	2006	NYSE	Entrepreneur
Yingli Green Energy	China	6.90%	2007	NYSE	Entrepreneur
Canadian Solar	China	5.80%	2006	NASDAQ	Entrepreneur
Hanwha SolarOne	China	5.30%	2006	NASDAQ	SOE Spinoff/ conglomerate subsidiary
JinkoSolar	China	5.00%	2010	NYSE	Entrepreneur
JA Solar	China	5.00%	2006	NASDAQ	SOE Spinoff /Join venture
ReneSola	China	4.10%	2006	NYSE	Entrepreneur
LDK Solar	China	0.60%	2007	NYSE	Join venture/ Entrepreneur
Suntech Power	China	5.8%*	2006	NYSE	Entrepreneur
Total*		40.3%			

Source: Bloomberg BISOLAR database.
* Suntech's market share is calculated based on 2011 data, the year before Suntech defaulted on its investor's bonds. Total market share does not include Suntech.

This dissertation aims to examine the causal relationship between the dependent variable production cost and the list of explanatory variables. A causal model illustrating the relationship among the factors is shown in Figure 2.3. It is hypothesized that subsidies measured in cost to access capital and equity, production capacity expansion, and increasing level of vertical integration all lead to lower solar PV production cost. Investment into R&D and higher production input cost, represented by electricity cost, would lead to higher PV production cost.

The causal impact of these factors in combination with each other and the data and method used to tease it out will be explored in details in Section 4.2.2 and 4.2.3 in Chapter 4.

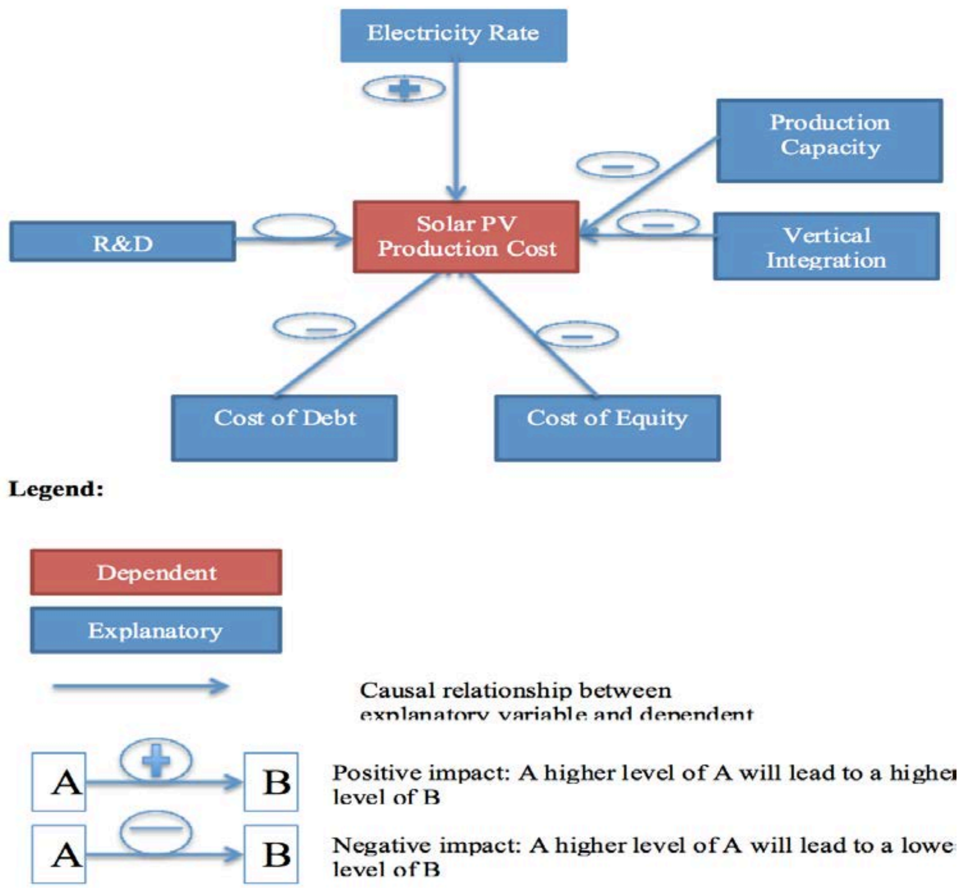

Figure 2.3 Causal Relationship Among Factors that Impact PV Production Cost

CHAPTER 3

THE SOLAR PV INNOVATION SYSTEM IN CHINA

3.1. Introduction

Solar PV technologies have come a long way since the early 2000s in terms of performance enhancement and cost reduction. The U.S. National Renewable Energy Laboratory (NREL) tracks the world record lab efficiencies of 24 types of PV technology between 1975 and 2015 (Figure 3.1). Over the 40-year time period, multiple types of new solar cell were invented and the electric conversation efficiencies of all of them rose significantly.

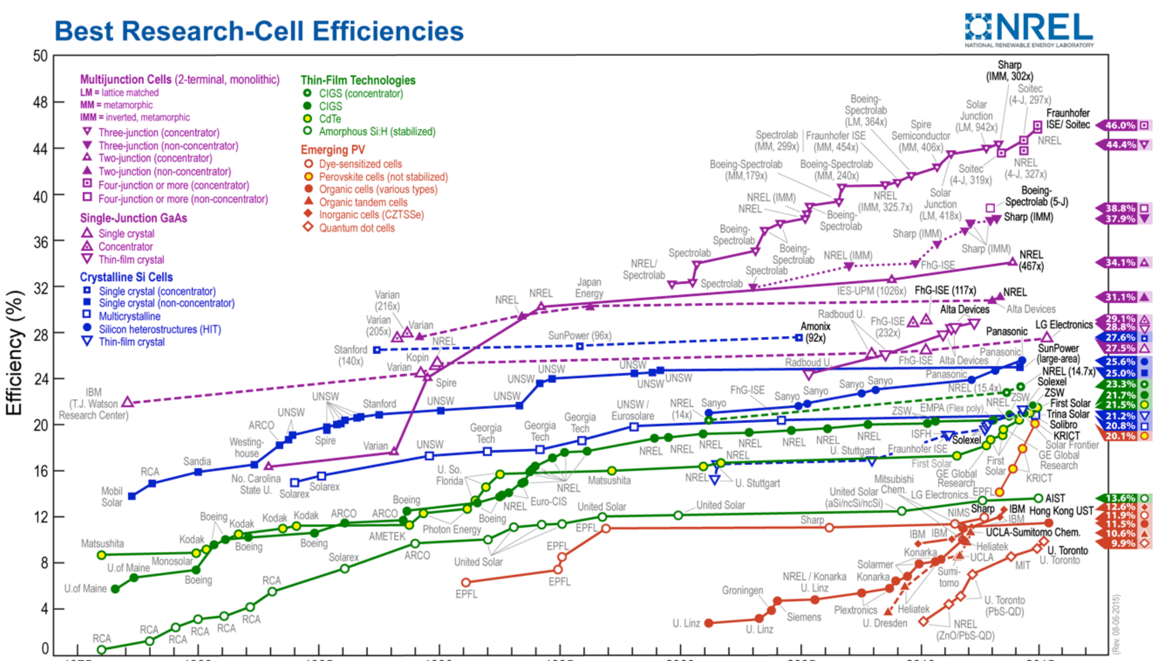

Figure 3.1 World Record Research-Solar Cell Efficiencies between 1975-2015
Source: The U.S. National Renewable Energy Laboratory
http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

In the meantime, the costs of solar panels have decreased dramatically. Figure 3.2 shows the cost trajectory of two types of commercially dominant solar PV panels, crystalline silicon (c-Si) panel and Cadmium telluride (CdTe) panel, over 33 years. Both technologies see their costs drop by more than a magnitude.

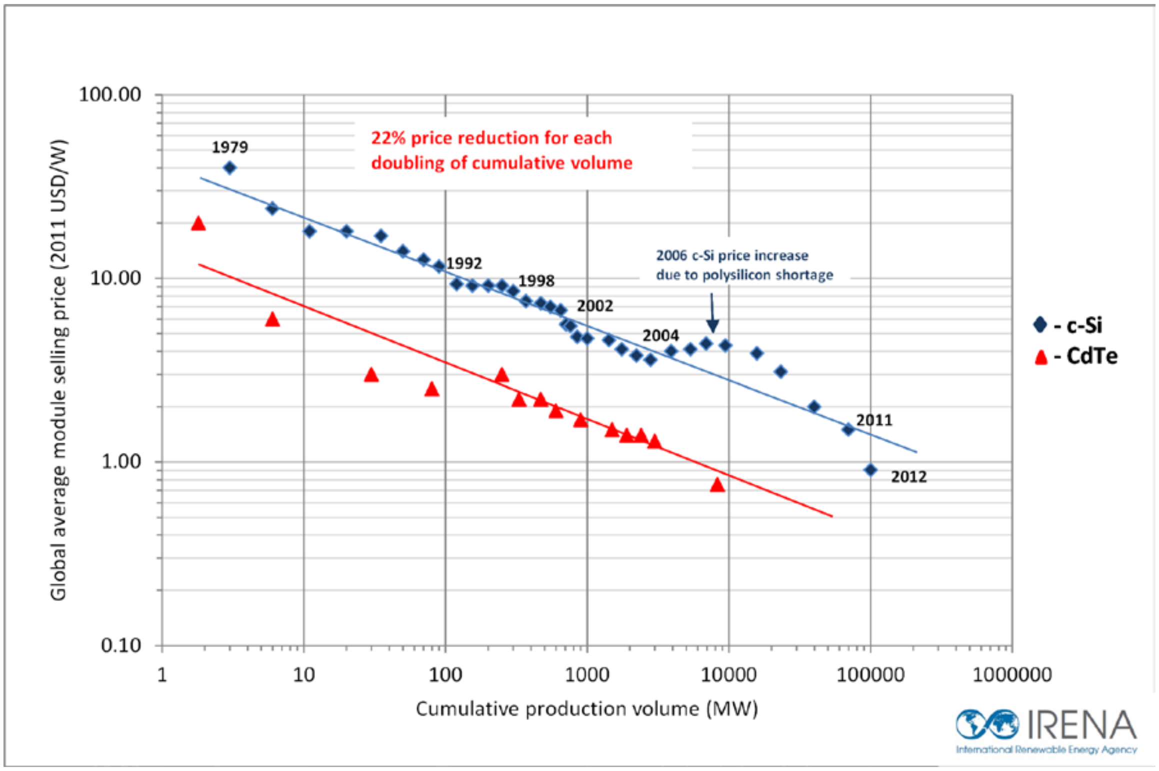

Figure 3.2. Global Average Solar Module Selling Price between 1979 and 2012
Source: International Renewable Energy Agency
http://costing.irena.org/charts/solar-photovoltaic.aspx

Scientific and technological innovation and manufacturing process innovation are the driving forces behind the performance and cost improvement. China's ability to manufacture solar panels at a large scale has contributed to the dramatic cost reduction (Goodrich et al., 2013a; Nahm & Steinfeld, 2014a). However, when it comes to innovation, China is a latecomer. It has a large historical knowledge gap compared to western innovation powerhouses like Germany, United States, and Japan. In fact, prior to 2014, none of the world solar cell efficiencies shown in Figure 1 was set by Chinese entities, until Trina Solar (known as Trina hereafter), – the world's largest solar panel producer, and a company based in China – broke the record for the multicrystalline solar cell. Despite the breakthrough, China is still seen as a weak innovator, especially in the hardcore science and technology areas. Acknowledging its weakness, China has devoted great effort to increase its solar PV innovation capability since the turn of the 21st century. This chapter intends to examine the innovation effort China made in three generations of solar PV cells, its effectiveness in producing innovation outcomes, and the mechanisms that lead to innovation progress or the lack thereof. The fundamental research questions this chapter seeks to answer is: **<u>Research Question 1a:</u> Where does China stand in terms of solar PV innovation relative to the world's leading innovators? And,**

<u>Research Question 1b:</u> what policies and market dynamics enabled or impeded the advancement of solar PV innovation?

Before diving into a detailed analysis, some easy-to-understand technical background about the solar PV technologies studied in this dissertation is helpful in terms of understanding the history of the technology and providing context.

Today, there are three generations of solar PV technologies. The first-generation of solar cells are silicon-based technologies. It includes mono-crystalline silicon (mono-Si) solar cell, poly-crystalline silicon (poly-Si) solar cells, amorphous silicon (a-Si) as well as a few high efficiency modifications of them such as Interdigitized Back Contact (IBC) cells, Passive Emitter Rear Contact (PERC) cells, Heterstructure with Intrinsic Thin Layer (HIT) cells, and etc. Compare to later generations, the first generation cells are based on silicon, a very common material on earth, and have relatively high conversation efficiency.

The second-generation technologies mainly include Copper Indium Gallium Selenide (CIGS), Cadmium telluride (CdTe), and etc. They are often called thin film solar cells because they are made by depositing one or more thin film-like layer of photovoltaic materials on a substrate. The second-generation technologies have lower efficiency than the first generation, but they are also cheaper to produce, which makes them legitimate competitors to their earlier peers.

Finally, the third-generation technologies refer to new and emerging solar cells such as organic PV (OPV), perovskite, dye-sensitized solar cell (DSSC), quantum dot solar cell, and Copper zinc tin sulfide (CZTS) cell. They are relatively new technologies but hold promising potential to reach high efficiency.

The remaining part of this chapter will first review the literature on innovation and generate a hypothesis pertain to the research questions. After providing an overview of the solar PV innovation actors, this chapter will proceed to answer the two research questions propose above by first assessing the progress made in the solar innovation system in China, and then dissect the strength and weakness of the system through examining its structure, actors' networks, and the mechanisms via which elements within the system interact with one another to produce innovation outcomes or the lack thereof. Guided by the TIS framework, the analysis does not only focus on understanding the ***structure*** of the system, the ***functions*** it fulfill, but also the ***process*** to fulfill the functions by identifying ***driving and blocking mechanisms***. Based on the findings, this chapter will close with some policy implications and recommendations.

3.2. Literature and Hypothesis

Scholars have long acknowledged that innovation is a nuanced concept. It does not only constitute the invention of brand new things, but also includes the improvements made to the "process". Richard Nelson defines innovation as "the processes by which firms master and put into practice product designs and manufacturing processes that are new to them" (Richard R. Nelson, 1993). Hardcore scientific and technological innovation is the act of inventing new technologies or new product that are either functionally or design-wise different from previous products. Often being misunderstood as the only form of innovation, scientific and technological innovation is a knowledge-intensive, capital-intensive operation and it is frequently associated with long planning period, sizable investment, and high risk (B Å Lundvall, 2010; Mitchell, 2010). For countries and firms alike, their ability to carry out scientific and technological innovation depends on hard criteria such as the knowledge and research skills of their people (Audretsch & Feldman, 1996) and soft environment like the society and company culture towards innovation and the policy environment (Huang et al., 2012; Mitchell, 2010; M. E. Porter, 1990a).

Unlike product innovation, process innovation has a murkier but also more encompassing definition. It refers to improvements of internal production processes, and discovery of new tools, devices and knowledge as well as customer based re-engineering. This can lead to higher product quality, higher labor productivity, less inputs requirement, lower production cost, and any combination of these outcomes (W. M. Cohen & Levinthal, 1990; Cohen, W. M., & Levin, 2007; C Freeman, 1987a). Process innovation is experience-based and is strongly related to the concept of “learning” (Arrow, 1962; Bengt Åke Lundvall, 2007; R R Nelson & Winter, 2009). There is a tendency in literature and in day-to-day thinking to overlook process innovation, or considered it not as important as “hardcore” product innovation. As Lundvall pointed out, this bias needs to be overcome because product and process innovation are interrelated, and latter is crucial to the former (Lundvall, 2007). Scholars also found that process innovation can be a significant source of firm competitiveness, which gives process innovation additional significance (Li, Liu, & Ren, 2006; Nahm & Steinfeld, 2014; Yam et. al., 2004).

Besides understanding the nuances about innovation, it is also crucial to realize that innovation is a network activity. At the macro level, the National Innovation Systems (NIS) framework championed by scholars like Nelson, Lundvall, and Winter has taken a system view by treating innovation activities as an interactive process through which multiple agents like universities, research organizations, firms, and government agencies engage in exchanges with each other under certain institutional settings (Bengt Åke Lundvall, 2007; Richard R Nelson, 1993). From a micro perspective, firms do not exist in isolation. Rather, they form innovation networks with research institutions like universities, research labs under the influence of or in partnership with regulatory bodies (Susan Christopherson & Clark, 2007). These innovation networks are key to the success of building innovative capacity and allow countries and firms to harness the return on innovation investment (Dooley, 2008; Energy Innovation, 2011; Huang et al., 2012; Bengt Åke Lundvall, 2007; Richard R Nelson, 1993; Nonaka & Takeuchi, 1995; Steinfeld, 2004; Teece, 1986).

The theoretical arguments for the network view of innovation are twofold. First, different parties offer unique resources that, when pooled together, are compliment to each other. For examples, universities have strong research capacity and personnel advantage but lack at real time knowledge about the market demands (Motohashi, 2005; Siegel, Waldman, Atwater, & Link, 2003). Meanwhile, firms have more information about market demands and better knowledge about process innovation that can be beneficial when combined with university resources (Ace & Audretsch, 2014; Motohashi, 2005; Nonaka & Takeuchi, 1995; Siegel et al., 2003). However, firms can be restricted by their pursuit of near-term interest, but governments have higher tolerant of risk and are in a position to make relatively long term investment (Dooley, 2008; K. Gallagher, 2013; Huang et al., 2012; Organization for Ecomonic Development and Coorperation, 1997). Together, firms, universities, and governments complement each other and allow greater efficiency in resource allocation and utilization (Etzkowitz & Leydesdorff, 2000; Motohashi, 2005).

Another reason why network is important to innovation is that it facilitates the diffusion of innovation. Technologies and knowledge flow not only within organizations but also across organizations. A network that connects academic researchers, innovators, entrepreneurs, firms, and government provide either formal or informal channels for information, technologies and knowledge to diffuse among interested parties. It lowers the transaction cost of diffusion (Carlsson & Stankiewicz, 1991; Williamson, 1999) and increase the likelihood of harvesting rents associated with innovation (Teece, 1986). Knowledge diffusion can also help break the spell of path-dependency (W. M. Cohen & Levinthal, 1990) and allow organizations to gain access to knowledge that would otherwise unable to develop indigenously.

Given the theories and literature, this work proposes the following hypothesis.

Hypothesis 1. Innovation networks facilitate knowledge production and diffusion, which lead to solar PV innovation progress in China.

As pointed out earlier, innovation is a multi-layered concept. As far as this chapter concerns, innovation is defined as hardcore scientific and technological research endeavor that lead to either new inventions or significant improvement to existing solar PV technologies. Chapter 4 will explore process innovation in greater detail.

3.3. Solar PV Innovation Actors in China

Innovation actors are one of the three key structural components of an innovation system in the lens of TIS, along with networks and institutions. It is important to understand whom the players are because they are the agents who conduct the actual R&D work; they form the networks and shape the institutions. They are like bones to an innovation system.

There are three types of key innovation actors in China's solar innovation subsystem: government agencies, research groups at university and research institutes, and R&D departments at private enterprises.

3.3.1. Government agencies

- Ministry of Science and Technology (MOST)

As China's science and technology policy-making body administered by the State Council, MOST is the main architect of the solar innovation TIS subsystem. It is principally in charge of setting national visions for science and technology development, designing substantive policies and strategies to promote the visions, and building innovation ecosystems and allocating financial resources to achieve the advancements desired by the visions. MOST does not work alone; it coordinates it financing and administrative efforts with other government agencies, introduced below.

- Ministry of Finance (MOF)

MOF provides public finance to MOST to be used for its various innovation programs. MOF also administers R&D related tax breaks and other forms of financial incentives. For example, MOF exempts research equipment purchased by research institutes and universities from import tariffs, value added taxes and sales tax.

- Ministry of Education (MOE)

MOE oversees universities, an important force of innovation in China. Although MOE is mostly in charge of university education, it shares the administrative responsibility of the university-based SKLs and SETRCs with MOST. Besides, MOE used to have its own SKL list, which is independent to MOST's SKL list. The MOE awarded SKLs receive R&D findings from MOE and will be evaluated by MOE on a five-year basis. However, since August 2015, as part of the overall national innovation system reform, MOE will no longer award its own SKLs in order to streamline the innovation spending and reduce redundancy.

- Ministry of Industry of Information Technology (MOIIT)

MOIIT is the nation's industrial policy-making body. Since MOITT's main constituency is the industries and companies, it works in concert with MOST to promote company-based R&D, technology commercialization, and incentive innovation in SMEs. This joint effort is particularly salient to solar technology innovation given the fact that a number of companies in the solar industry such as Trina, Yingli Solar (known as Yingli hereafter), and GCL-Poly are active in conducting R&D. MOIIT aims to facilitate the solar PV companies to better integrate their R&D efforts with production and bring new products to the market. In addition, MOIIT also influences solar PV innovation through issuing industry standards. The Solar PV Manufacturing Industry Standards rolled out in

2013 by MOIIT requires a minimum 3% of company's revenue and no less than ¥10 million ($1.6 million) every year on R&D.

- National Development and Reform Commission (NDRC)

NDRC is in charge drafting the national Five Year Plans (FYPs) and other economic policies. As an integral part of the national economy, science and technology development is frequently mentioned in FYPs, especially since the 1980s. NDRC sets grand goals for S&T development in the FYPs. The goals will later be further articulated by MOST via its own sub-FYPs.

In addition to drafting the nation's economic policies, NDRC also oversees the National Energy Administration (NEA), which is the central government's energy policy-making body. It is in charge of deploying solar energy and supports research related to solar PV system and grid connection.

This multi-agency approach led by MOST is mirrored, to a large degree, at the provincial and local level. Each Chinese province has its own Bureau of Science and Technology (BOST), and it works with the provincial counterparts of the other central government agencies to promote innovation activities in their jurisdiction. Similar structure trickles down even one more level to local governments.

3.3.2. Research Groups at Universities and Research Institutes

The role played by research groups at universities and research institutes in China's solar innovation system cannot be overstated. Historically, government affiliated research institutes were the first generation solar PV research entities. Nowadays, research groups at universities and research institutes conduct some of the most basic science and engineering research (***knowledge development and diffusion***). Table 3.1 summarizes major research groups from both the public and private sector in nine research areas across three generations of technologies.

It shows that academics completely dominate the third-generation technology research field. Compared to previous generations of technologies, third-generation technologies like perovskite and organic solar cell are still at the early stage of technology development and not considered as market-ready yet. Therefore, private sector actors are still waiting to see if there is a realistic chance of commercializing these technologies. In contrast, academics at universities and research institutes are well suited to lead the charge of scientific investigation in these areas because of their basic-research oriented focus. It is worth noticing research in this space is mainly lead by young researchers with overseas education background. The third-generation solar cell research in China benefited from harnessing the power of globalization. The rigorous research training these young academics received abroad, their acute intuition about the latest research trends, and their English communication skills make them agents of change to solar innovation in China. They directly contribute to the narrowing of the innovation gaps between China and the world class in the third-generation of solar technologies. More details about the research conducted in these research entities can be found in Section 3.7.2 and in Appendix B.

Table 3.1 Major Solar Cell Research Groups in China

<table>
<tr><th colspan="2">Technology</th><th>Major Public Research Groups</th><th>Major Company-based Research Group</th></tr>
<tr><td rowspan="7">First Generation Technology</td><td rowspan="5">Crystalline silicon solar cell</td><td>Chinese Academy of Sciences (CAS) Institute of Electric Engineering</td><td>SKL at Trina</td></tr>
<tr><td>Shanghai Jiaotong University</td><td>SKL at Yingli</td></tr>
<tr><td>Zhongshan University</td><td>Canadian Solar</td></tr>
<tr><td>18th Research Institute of CETC</td><td>JA Solar</td></tr>
<tr><td>811th Research Institute of CETC</td><td>Jinko Solar</td></tr>
<tr><td rowspan="2">Material and Tooling for crystalline silicon solar cell</td><td>48th Research Institute of CETC</td><td>GCL-Poly</td></tr>
<tr><td>45th Research Institute of CETC</td><td>SETRC at LDK</td></tr>
</table>

Table 3.1 Continued

		Major Public Research Groups	Major Company-based Research Group
		42th Research Institute of CETC	Shenzhen S.C.
		CAS Fujian Institute of Research on the Structure of Matter	Seven Star
			Fullshare Energy
	HIT	CAS Shanghai Institute of Microsystem and Information Technology	SKL at Trina
		CAS Institute of Electric Engineering	
	PERC		Sunergy
	Amorphous silicon solar cell	Nankai University	
		CAS Institute of Electric Engineering	
		Zhengzhou University	
Second Generation Technology	CIGS	Nankai University	Global research centers of Hanergy
		CAS Shenzhen Institutes of Advanced Technology	
		CAS Shanghai Institute of Ceramics	
		CAS Shanghai Institute of Microsystem and Information Technology	
		China Science and Technology University	
		Tsinghua University	
		Peking University	
	CdTe	Sichuang University	Advanced Solar Power (Long Yan)
		CAS Electric Engineering Institute	
		CAS Shanghai Institute of Technical Physics	
		China Science and Technology University	
	GaAs	18th Research Institute of CETC	
		811th Research Institute of CETC	
		CAS Suzhou Institute of Nano-tech and Nano-bionics	

Table 3.1 Continued

Technology		Major Public Research Groups	Major Company-based Research Group
Third Generation Technology	Organic solar cell	CAS Institute of Chemistry	
		South China University of Technology	
		Peking University	
	Perovskite	Huazhong University of Science and Technology	
		Peking University	
		CAS Institute of Physics	
		Tsinghua University	
		CAS Changchun Institute of Applied Physics	
		Dalian University of Technology	

In contrast, research groups working on the first-generation solar cell technologies are more likely to adopt a practical approach to their work in two ways: they either team up with solar PV manufacturers to develop technologies of high commercializability, or they work with them to solve tooling and material obstacles faced by the manufacturers.

The practical mindset makes them often place high priority on the industry-applicability of their R&D products. Their no longer only concern how to overcome the scientific and technical barriers, but also to keep a close eye on product commercialization. They do so by designing simpler cell structures and using cheaper materials to control the production cost. Although cell efficiency may also be lowered as a result of these approaches, it does not discourage the researchers. During interviews, many of them showed the belief that the person who gets the last laugh is the one whose technology is sold on the market rather than the one who sets the highest efficiency records[3].

Research groups working on the second-generation solar cell technologies are in the middle ground between basic and applied research. There are a large number of CIGS

[3] Interviewee #39, #45, #59, #73

research groups, and some of them, such as the labs at Nankai University, are among the first movers in solar cell research. However, the commercialization space in China is dominated by silicon-based technologies, domestic Chinese CIGS technologies have not been able to garner enough cloud to achieve mass production yet. An attempt by Nankai University to start a joint-venture company with private sector partners to produce its own technology ran into big financial and operational issues. The company ended up going bankrupt without even producing a single cell. The case with Nankai University illustrates the difficulties in commercializing CIGS in China. As a result, most research groups choose to stay focused on researching the fundamentals related to CIGS, and the efficiency of the technology increased dramatically in the past one and a half decades. Section 3.4.1 will discuss the efficiency performance of various types of solar PV technology including CIGS.

There are not a lot of groups in China conducting CdTe research. The slim chance of CdTe commercialization is a major deterrence factor. According to interviews with Chinese researchers and company officials, China's domestic solar industry has not been excited about CdTe because of two concerns. First, Cadmium's environmental impact on water may invite tighter environmental regulations and impose higher compliance costs. Second, Tellurium is a rare element and mass-utilization may cause a sharp decline of its availability and drive up the cost. Since researchers in China often have an eye towards technology commercialization, they are, discouraged by the difficult path for CdTe commercialization, resulting a mundane research interest and a slower efficiency improvement[4].

3.3.3. Corporations

Corporate R&D is playing an increasingly important role in China's solar innovation system for two reasons. First, the central government has a strong desire to

[4] Interviewee #47, #52, #93

mobilize private sector players to step up their innovation efforts because they do not only have the financial resources to do so but also the first-hand information about the market for technologies and its demand for innovation. One major criticism about the solar innovation system as MOST manages is that there is a big disconnection between the types of research academics does and the types of research the solar industry needs. It is not rare to find cases that research projects handpicked by MOST ended up being regarded as too theoretical or tangential by the solar companies and do not a stand a chance of generating economic returns. For example a-Si and DSSC are among the technologies that receive long-standing MOST investment, but their commercialization is far from sight. In order to increase the efficacy of its R&D investment and facilitate information sharing among academic researchers and the industry, MOST started to encourage joint R&D between academia and the industry since the 11^{th} FYP cycle. In the 12^{th} FYP, MOST escalated the status of corporations to the "main agent" of China's national innovation system, and stated that market, not the government, should play a bigger role in R&D resource allocation. All these official rhetoric meant to send a policy signal to private sector players and make them more active in R&D.

Besides the inviting signal from the central government, private sector players in China have innate drives to invest in innovation to enhance their market competitiveness. This is particularly true for Chinese solar PV manufacturers after the trade disputes with the U.S. and E.U (see Chapter 5 Section 5.2.3 for more information about the trade dispute). After a period of rapid cost reduction between 2009 and 2013, the cost of solar PV hit a plateau and consumers shifted from looking for cheap solar panels to pursing better quality and more reliable panels. On top of this changing trend in the consumer market, the import quota and price floor imposed by the E.U., and tariffs charged by and U.S. also resulted in shrinking cost competitiveness for Chinese PV producers. In response, large Chinese PV manufacturers turned to innovation for their next source of competitiveness.

In 2013, two State Key Labs opened their doors at two Chinese companies: Trina and Yingli, respectively. All publicly traded Chinese PV manufacturers have their own in-house R&D divisions, and they regularly devote human and financial resources to their R&D activities. Table 3.9 in the innovation investment section lists Tier 1 Chinese PV companies and their annual investment in R&D. PV companies are the major contributors to the first generation solar technology R&D in China. They eclipse academic groups in both R&D investment and R&D output, measured in cell efficiency improvement.

Exhibit 1 and 2 in Appendix B showcase the R&D activities at Trina and Yingli's SKLs. Exhibit 3 in the Appendix provides an overview of Canadian Solar's innovation effort, which represents a middle of the road corporate innovation model in China, unlike the "glamorous SKL model". Exhibit 4 offers a view into the innovation related to PERC cell at Sunergy, the first mover in PERC solar cell research and commercialization in China. Innovation effort at Advanced Solar Power (ASP, known as Long Yan in Chinese), the leading innovator and producer of CdTe solar PV in China, is summarized in Exhibit 5.

One thing to notice is that, besides establishing their own R&D department, silicon PV producers in China often build their research network by collaborating with academic researchers. For example, Trina works with Dr. Zhengxin Liu from CAS Shanghai Institute of Microsystem and Information Technology on HIT research; Chaori Solar works with Dr. Wenjing Wang from CAS Institute of Electrical Engineering also on HIT. The nature of company-academic research in China is more science-oriented than most of the R&D conducted in-house at Chinese companies. (Section 3.7.2 details the research networks).

Hanergy, China's largest thin-film solar cell producer, represents a very different network model. Instead of building its indigenous innovation capacity, the company has garnered R&D strength through a list of high profile global merge and acquisition. It acquired five overseas innovative thin film solar PV companies and became the owner of their R&D profiles (Exhibit 6 in Appendix B details the companies Hangery purchased and their technology profiles). Its global R&D center in Beijing is the central management entity that oversees its global research network. No actual research is conducted in its Beijing center. In Hanergy's model, the goal was not so much to build an indigenous innovation capacity, but to build a global research network through acquiring overseas promising thin film technologies that struggle with commercialization and marry them with China's strong manufacturing capacity.

3.4. Evaluate Solar PV Innovation Progress in China

A technology system's innovative capacity can be measured using both the output of the system and the input into the system (Ace and Audretsch 2014; Freel 2000 Arnold 2004; Georghiou and Roessner 2000; Griliches 1979; Salter and Martin 2001). This study first uses world and Chinese record solar cell efficiencies, quantity and quality of sola PV related patents, and scientific publications to measure the outputs of the solar PV innovation system in China. Later, R&D investments from the public and private sector are analyzed. Rather than treating the investment as merely an input into the system, it is found that the investment is actually a driving force in producing better system output.

3.4.1. PV Lab Efficiency – Measure the Innovation Output

Solar cell efficiency is the most important indicator of the innovative capacity of a solar innovation system. Using five types of solar cell from three generations of technology, this study measures the progression of record cell efficiency in Chinese and compares it to the evolution of the world records. Improvements in record Chinese solar cell efficiencies serve as a proxy for solar PV innovation progress produced by the system. Furthermore, the change in the gap between Chinese record efficiencies and the world record efficiencies indicates the relative strength of China's solar PV innovation capacity in relationship to the world's leading innovators'. For example, in all five technologies, record efficiencies were lower in China at the beginning. If over time, the gap between the China and the world’s leading level narrows, it then suggests that China’s solar innovation strength has grown relatively and vice versa. The results show three different trends, which are discussed below.

3.4.1.1. Gaps are Narrowing in HIT and CIGS

Heterstructure Intrinsic Thin-layer, a.k.a. HIT, is a high efficiency first-generation solar PV technology. It takes advantages of both the high efficiency of crystalline silicon and the thin layer of thin film. Copper Indium Gallium Selenide (CIGS) is the most popular second-generation solar PV technology known for its light weigh and low cost.

Figure 3.3 and 3.4 tracks the world record HIT and CIGS cell efficiencies and those in China over the decades. For both technologies, the efficiency boundaries keep moving forward, internationally and within in China. Furthermore, there was a large historical efficiency gap between China and the world’s leading innovators for both HIT and CIGS. However, the gaps become narrower over time, with China closing in to the world-class level. The continuously improving efficiency records in China suggest that the Chinese solar PV innovation system has been producing progress in the HIT and CIGS technology space. What is more, the narrower efficiency gaps indicate that the Chinese’ ability to produce high efficiency HIT and CIGS cell is catching up to that of the world’s leading innovators. Both pieces of evidence show that China is growing its innovation capacity related to these two technologies and is improving its relative innovation strength compared to the world-class.

A further look at the innovation actors who produced the Chinese records and their research collaborations suggest that innovation networks are at the heart of the cell efficiency improvement. Later in Section 3.7.2, a detailed network analysis will be carried out to dissect the relationship between the innovation networks and the outcomes that the system produces. But just to foreshadow the findings, the improvement in HIT cell efficiency in China is a result of both industry-academia collaborative R&D efforts supported by MOST and by harnessing the power of the increasingly globalized innovation network, while the Chinese CIGS innovation network leverages the knowledge and methodological advantage of oversea-educated Chinese scientists.

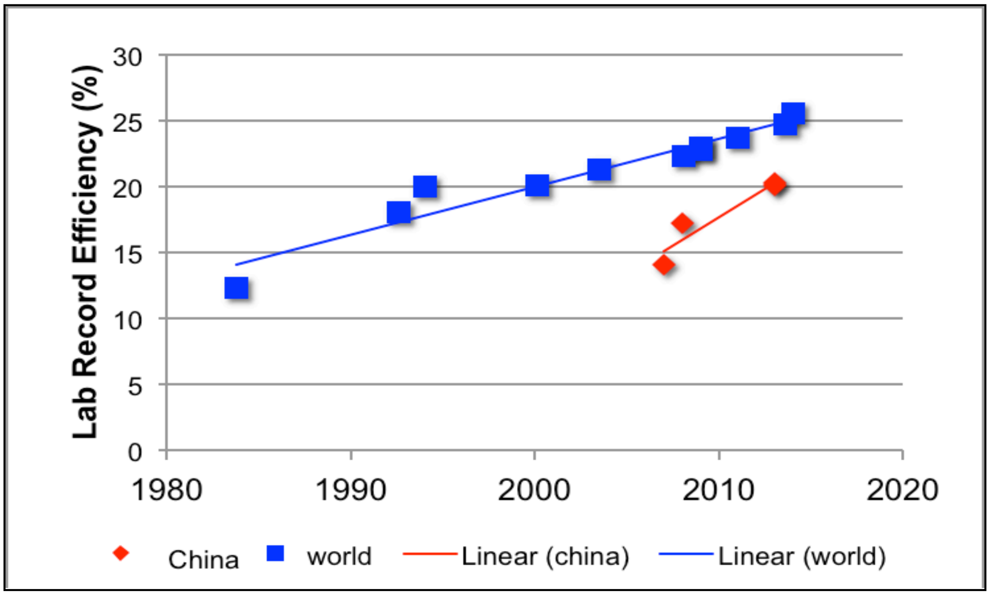

Figure 3.3 World and Chinese Record HIT Research-Cell Efficiencies*

* See Exhibit 7 in Appendix B for detailed information on each data point.
Data collection and analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
Information presented at Stanford China Project workshop in Washington DC.

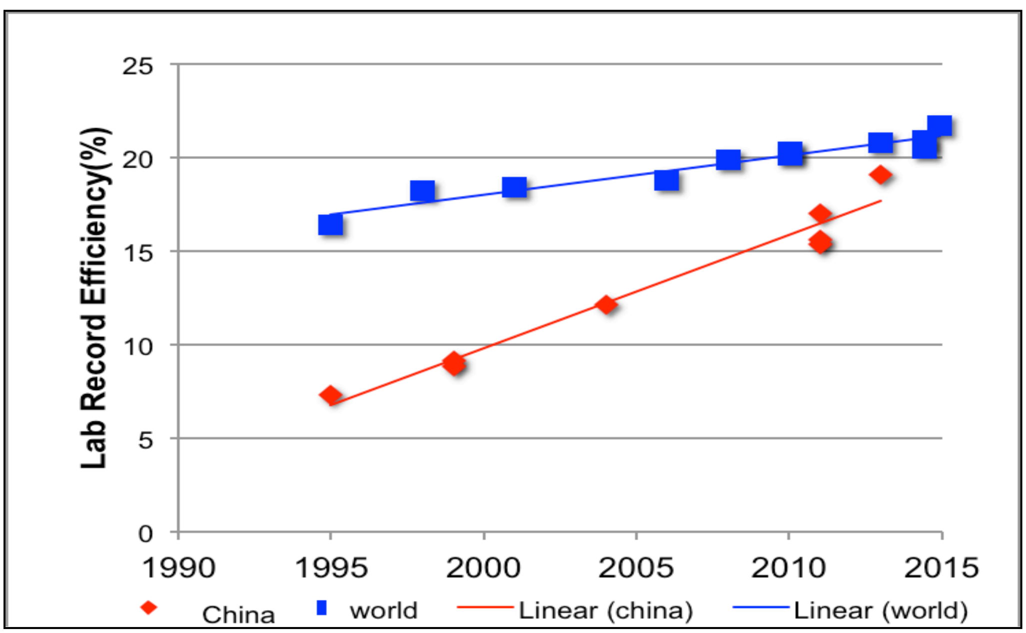

Figure 3.4 World and Chinese Record CIGS Research-Cell Efficiencies*

* See Exhibit 8. In Appendix B for detailed information on each data point.
Data collection and analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
Information presented at Stanford China Project workshop in Washington DC.

3.4.1.2. Miniscule Gaps in Perovskite and Organic PV

For technologies like perovskite and organic PV, China had a small gap to begin with because they are relatively new technologies and China does not have a historical knowledge gap that it needs to overcome. Although China entered perovskite research relatively late, the record efficiency leapfrogged when multiple research groups enter the area and created competition among themselves (Section 3.7.2.5). As a result, Chinese record efficiency was updated 9 times by 8 different research groups in 16 months and eventually stood at 15.4% in April 2014. Similarly, two competing Chinese groups keep updating OPV record efficiency in China. The density of the data point in Figure 3.5 and 3.6 show the active perovskite and organic solar PV research space in China, as well as globally. Once again, innovation networks are key to the rapid improvement of cell efficiencies. Scholars with ties to leading overseas research institutes drove the progress in these two technologies, as Section 3.7.2.4 will explain in detail. Besides, large amount of grants coming form NSFC's to these two research area certainly enhance the research capacity in these two technology areas (Section 3.6.3.1).

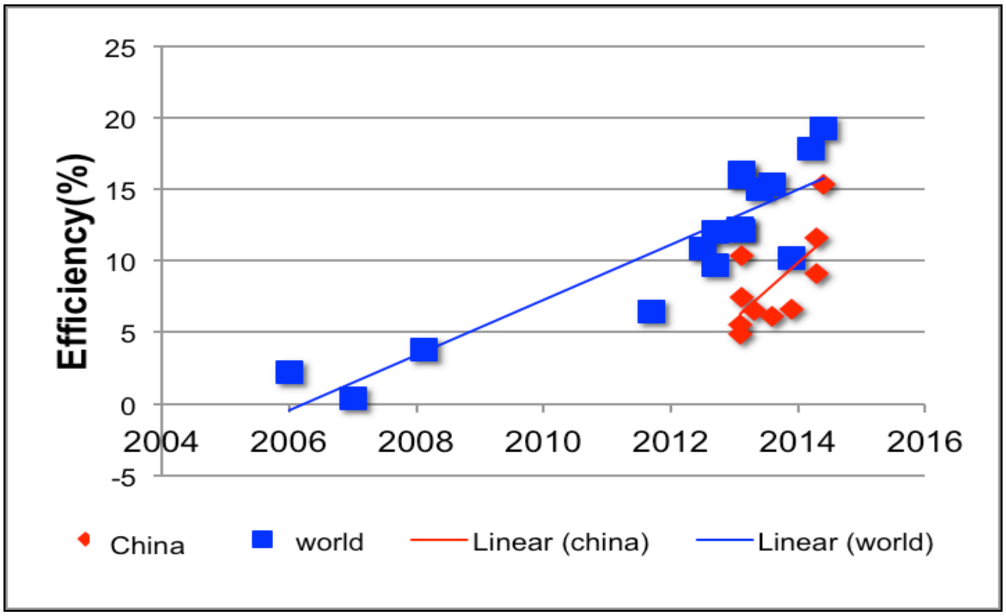

Figure 3.5 World and Chinese Record Perovskite Research-Cell Efficiencies*

* See Exhibit 9. In Appendix B for detailed information on each data point.
Data collection and analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
Information presented at Stanford China Project workshop in Washington DC.

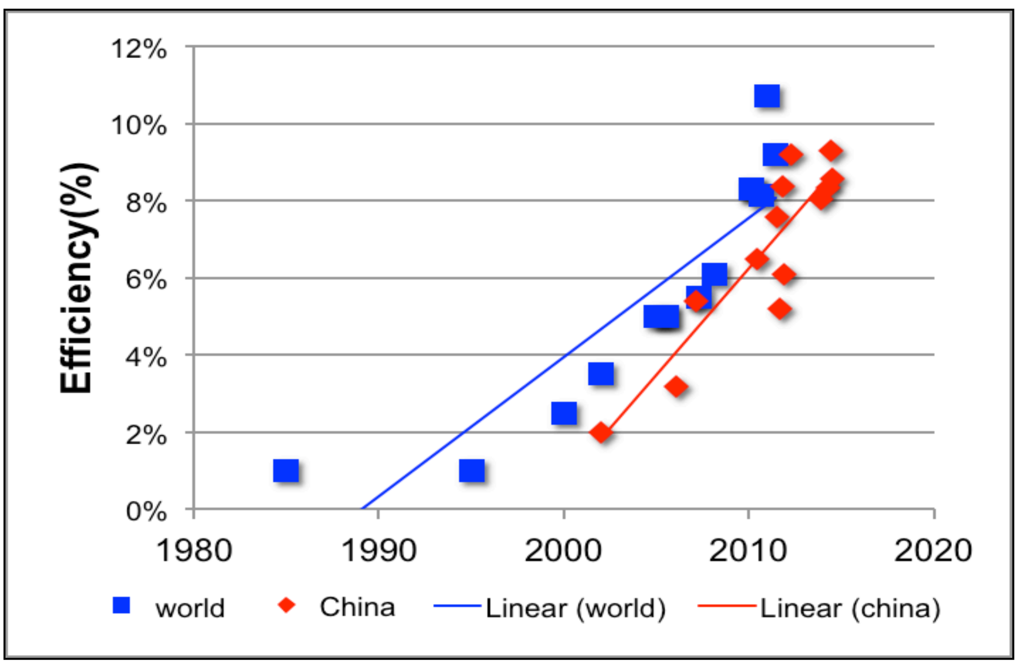

Figure 3.6 World and Chinese Record Organic PV Research-Cell Efficiencies*

* See Exhibit 10 in Appendix B for detailed information on each data point.

Data collection and analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
Information presented at Stanford China Project workshop in Washington DC.

3.4.1.3. Large Gap Remains in CdTe

The research space of CdTe is not as active as that of the previous four technologies. Due to concerns for cadmium's environmental impact on water quality and tellurium's lack of natural availability, CdTe research in China has not been able to create a large enough academic cloud to produce innovation progress. Only a small number of research groups work on CdTe (Table 3.1). As a result, the gap between China and the world remains significant in this area, as shown in Figure 3.7.

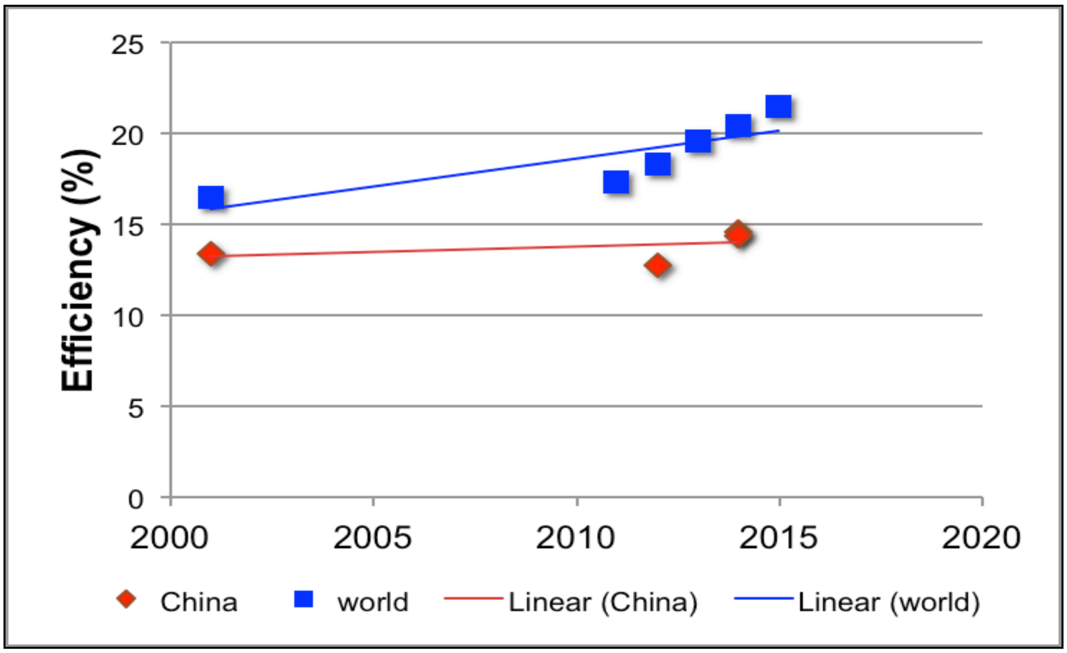

Figure 3.7 World and Chinese Record CdTe Research-Cell Efficiencies*

* See Exhibit 11 in Appendix B for detailed information on each data point.
Data collection and analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
Information presented at Stanford China Project workshop in Washington DC.

Using the solar cell efficiency of five types of technology as an indicator, this study arrives at two findings. First, the solar PV innovation system in China has made progress in improving its capacity, as suggested by the continuously rising solar cell efficiencies in all technology categories. Second, the gaps between China and the world's leading innovation have narrow for most technologies but not CdTe. This indicates that although the improvement in innovation strength is uneven across technologies, in general, China is catching up to the world-class level.

3.4.2. PV Patents – Measure the Innovation Output

Solar innovation is a multi-faucet concept and its measurement is not limited to laboratory cell efficiency. Patent is another good candidate to measure innovation because it provides a relatively objective measure of new knowledge. A successful invention patent must demonstrate something novel, something that is not previously known or mastered. A patent ideally should show the state-of-the-art techniques in its field and is agreed by experts to be nascent and innovative (Albert, Avery, Narin, & McAllister, 1991; Alcacer & Gittelman, 2006; Basberg, 1987).

There are three types of patents in China: invention patent, utility model patent, and design patent. Among the three, invention patents are considered to have higher innovative quality because applicants need to meet a set of stringent standards in terms of novelty and creativity in order to be granted an invention patent. This study analyzed solar-PV related invention patents granted by China's State Intellectual Property Office (SIPO) between 2000 and 2014.

3.4.2.1. Patent Quantity as An Indicator of Innovation

Analysis of China SIPO's data shows that Chinese players are filing and obtaining more and more solar PV-related patents. Both the total number of patents and the growth rate are greater for Chinese players than those for foreign entities. As seen from Figure 3.8, the number of patents granted to Chinese entities was very small in the first half of the 2000s. Chinese entities obtained less number of patents in its domestic market than all foreign entities combined. However, 2007 was as a watershed year. The number of patents granted to Chinese entities rose rapidly since then and quickly surpassed the foreign entities' patent numbers. Figure 3.8 tracks the number of patents granted by their application year[5].

This steep upward trending line does not mean Chinese players are more innovative than their foreign counterparts. Instead, it is a piece of evidence showing that Chinese innovation players have devoted significant effort in the past decade to produce patent-worthy knowledge and products.

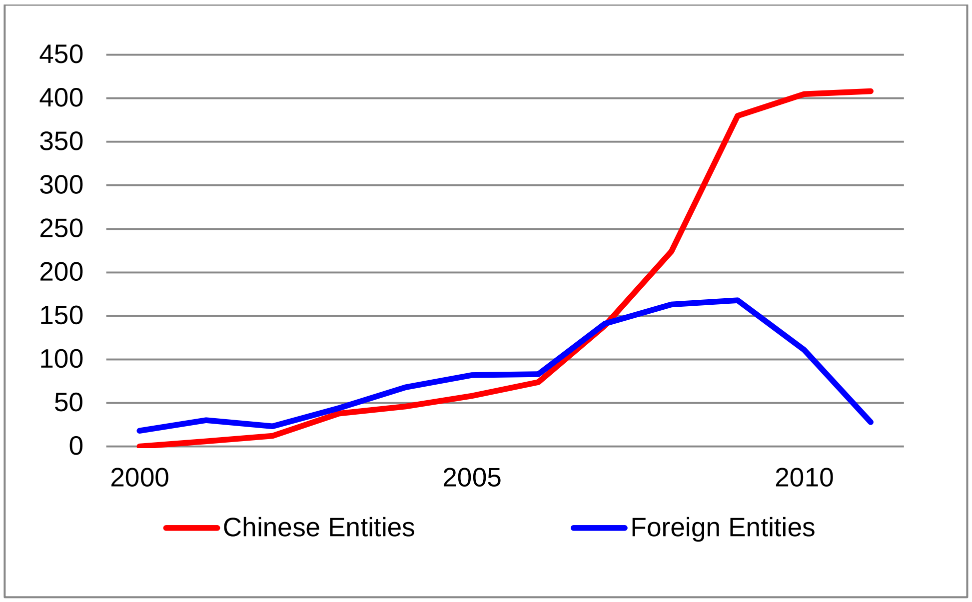

Figure 3.8. Patents Granted in China*

[5] The time horizon ends on 2011 because of the following reason. This study focuses on patents granted rather than patent applications and it usually takes 2 to 3 years for a patent to pass the evaluation process. Therefore, majority of the patents granted in 2014 were filed in 2011 or earlier, which correspond to the time horizon of the chart.

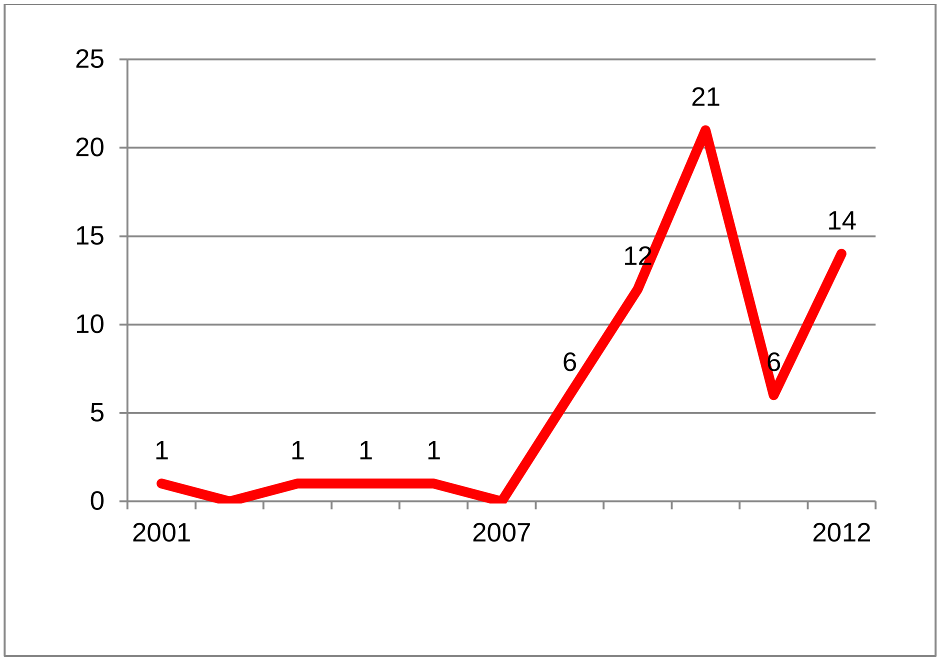

Figure 3.9. Patents Granted in the US to Chinese Entities*

*Data source: Figure 3.8: State Intellectual Property Office (SIPO) of P.R.C. http://www.pss-system.gov.cn/sipopublicsearch/ensearch/searchEnHomeIndexAC.do
Figure 3.9: United States Patent and Trademark Office (US PTO) http://www.uspto.gov/patent
Data collection for Figure 1 facilitated by Evalueserve http://www.evalueserve.com/
Data collection and analysis done as part of Stanford University China Project.
Information presented at Stanford China Project workshop in Washington, DC.

Granted, there is a home field advantage when looking at patents granted to Chinese entities in China. To correct that basis, this study also analyzed solar PV patents grated in in the U.S. Figure 3.9 shows the number of solar PV patents Chinese entities obtained in the U.S., charted by their application year. Two observations can be made. First, the number of patents granted to Chinese by the U.S. PTO is significantly smaller than it is by the China PTO, as shown in Figure 3.9. In total, only 65 patents have been obtained by Chinese inventors over the past 15 years, compared to over 1400 patents obtained by American inventors (not charted due to the high volume). Despite the smaller number, the trend shown by the US PTO data is similar to the patent data in China: the number of patents obtained was small before 2007 and it spiked since then. 2011 appears to be an abnormal year with a dip in number of patent granted. However, this could be due to the time lag between patent application and issuance and therefore, it should be seen as only a temporary drop.

To understand the reason behind the big spike in number of patents obtained by Chinese entities, one must take a close look at innovation policies in China. Two major policies played a significantly role in shaping the patent regime and players' patenting behavior in China. In 2008, the State Intellectual Property Office (SIPO) of China issued an Outline of the National Intellectual Property Strategy (SIPO, 2008). Its overall goal is to "improving China's capacity to create, utilize, protect and administer intellectual property, making China an innovative country". Among the four goals laid out by the Outline, the number one goal is to increase the percentage and absolute quantity of the self-relied intellectual property and make China rank among the advanced countries of the world in terms of the annual number of invention patents granted to the domestic applicants and also raise the number of overseas patent applications filed by Chinese applicants. The outline also declared that policies related to finance, investment, government procurement, industrial development, and etc. would be used to facilitate the creation and utilization of patents. New energy technologies including solar are listed as one of the key areas for patent creation and utilization. In 2010, National Patent Development Strategy for 2011-2020 was promulgated to improve the country's innovation strength and further enhance China's ability to utilizing patent system and resources (SIPO, 2010). Incidentally, a few science, technology and innovation (STI) programs under MOST, such as the 973 and 863 program, encourage or even require the projects they support to produce certain number of patents.

The timing of the issuance of the Outline and the National Strategy also correlates with the uptake and strong growth of the Chinese patent numbers in China and in the U.S. One could argue that the dramatic increase in the number of patents granted to Chinese in China is because the Outline explicitly encouraged the creation of patents, in which it sent a signal to both the innovation players for them to work harder to create patent-worthy material and to the intellectual property administrators for them to approve more patents. However, a similar uptake in patent numbers can also be observed in the number of patents granted to Chinese entities in the U.S. (Figure 3.9). It is fair to assume that American patent administers are not under any pressure to increase the number of Chinese-owned patents, which is to say that the increase in Chinese patents in the U.S. is mostly due to a higher level of innovation among Chinese inventors. Using the combination of Figure 3.8 and 3.9, one can conclude that although Chinese policies had created a favorable environment for Chinese players to obtain patents in its domestic market, the larger number of Chinese patents is not merely a result of loosing approving process. Instead, it, in part, demonstrates the country's improvement in solar PV innovation capacity.

Government policies certainly led to a large increase in patent filing in China and made it the world's number one in the number of patent applications by the end of 2012 (United Nations, 2012). For example, if a company owns a large number of patents and has a high-level of R&D spending and a well-educated R&D team, it could obtain recognition of the High and New Technology Enterprise and obtain tax credits given to companies. Policies like this, along with national IP strategies, to certain extent incentivized innovation players to file for patents, which in turn led to greater number of patents. However, critics see the increase in patent numbers as a bubble because it is in part driven by policies. Aware of the criticism, Chinese government is changing the system to improve the quality of patent filings without reducing the numbers. For example, SIPO has issued a policy to evaluate the novelty of utility models in order to avoid granting patent rights to copy cat patents. Many local governments such as Shanghai, and Suzhou have started to organize technology committees to evaluate the quality of patents in a more comprehensive way, in order to avoid granting preferential tax status simply based on the number of patents.

3.4.2.1.1. A technology-by-technology look at patents

A detailed technology-by-technology analysis shows that Chinese players and foreign players focus on the similar areas of research. For instance, five out of the top seven PV technologies by number of patents granted to Chinese and foreign entities are the same; organic solar PV, mono-silicon, DSSC, poly-silicon, and CIGS are among the common interests between Chinese and non-Chinese players.

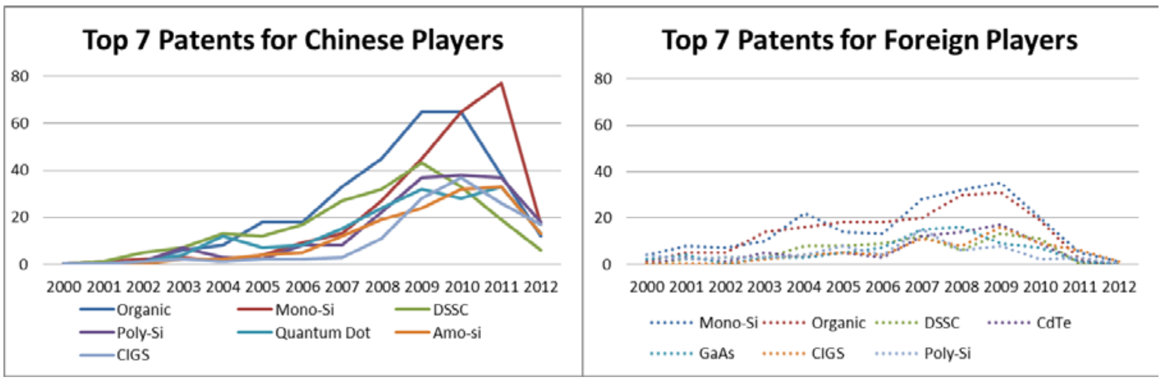

Figure 3.10 Top 7 Technologies for Chinese and Foreign Players in terms of Number of Patents Granted

*Data source: Figure 3.10: State Intellectual Property Office of P.R.C. http://www.pss-system.gov.cn/sipopublicsearch/ensearch/searchEnHomeIndexAC.do
Data collection and analysis done as part of Stanford University China Project and facilitated by Evalueserve http://www.evalueserve.com/

Using the progress made by Chinese entities, PV technologies can be divided into three categories.

Category 1: Chinese entities have caught up with and even surpass western players in mono-si, poly-si, a-Si, HIT, CIGS, CdTe, PERC, pervoskite, GaAs, Metal Wrap Through (MWT), Multi-junction. Similar to the historical efficiency gap in HIT, CIGS, and CdTe technology, there had been a gap in number of patent held in the above mentioned technologies between China and its western peers in technologies in this category. However, overtime Chinese players did not only closed the gap, they surpass western players in number of patents obtained.

Technologies in category 1 can be further divided into two groups: a group that represents first- and second-generation conventional PV technologies including mono-Si, poly-Si, a-Si, HIT, CIGS, CdTe, PERC; and a group that represents new and emerging technologies like pervoskite, GaAs, Metal Wrap Through (MWT), Multi-junction. The reasons for the rapid patent number growth for these two groups are different. For first- and second-generation technologies, because they are the predominant commercial technologies on the market, they benefit from corporate R&D investment more than any other innovation sources. Chinese companies accounts for majority of the patents in this group, indicating that they are the driver in technology innovation of the conventional PV technologies and their high-efficient derivatives like HIT and PERC. For the new and emerging technology group, Chinese academics carry the weight of innovation and are responsible for majority of the patents granted. It makes sense because these technologies are still at their early R&D stage; they are not market-ready yet, which makes them perfect candidate for academic research.

<u>Category 2</u>: In technology areas such as organic, DSSC, Quantum Dot, CZTS, Chinese players were leaders from the very beginning, filing and obtaining more patents than their foreign counterparts since as early as 2001. Parallel to what was observed in the cell efficiency analysis, this patent analysis shows that China's organic solar cell research moves almost head-to-head with world's leading countries from the very beginning. Research personnel exchange between China and the U.S. early on in the invention and initial development stage of the technology had allowed China to stay on top of the latest development of the technology and in so doing avoided getting a late start. In general, China does better with newer technologies, as suggested by organic PV, as well as DSSC, Quantum Dot, CZTS, of which Chinese academic filed for more patents than foreign entities from the very beginning.

<u>Category 3:</u> Chinese players are still slightly behind their foreign counterparts in IBC. IBC is the flagship high-efficient product of Sun Power in the U.S. Deterred by both

of the high knowledge barrier to product IBC and the concern for direct competition with Sun Power, Chinese companies have made the strategic decision to not pursue the IBC line of research and product development. As a result, IBC research is not active in China and has produced few patents.

More details on patents can be found in Appendix B Table B.2.

3.4.2.1.2. Patent behavior by different actors

In general, universities and research institutes are leaders in obtaining patents in the new and emerging technology areas (Table 3.2). These technologies are still at early research stage and therefore, have not received much R&D interest from the private sector. Nevertheless, they are perfect candidates for academic research because of the need to understand the underlining science and engineering related to these technologies. In contrast, companies hold the majority of the patents for a suite of technologies that have already been commercialized or with near term commercialization potentials, such as mono-si, poly-si, a-Si, HIT, CIGS, PERC, and IBC.

Our results suggest that there is a division of labor between public sector R&D and private sector R&D (true for both patents and efficiency), which suggests the PV innovation system in China is rational and relatively efficient. It is rational because researchers from universities and research institutes and their counterparts at private companies' R&D division do what they are each incentivized to do. Depending on the market-readiness, the academics are more likely to work on early-stage technologies because scientific inquiry is their job, whereas private sector companies, driven by the market and profit motives, conduct research related to commercial and commercializable technologies. By focus on largely different areas of the PV technology spectrum, public and private sector innovation players in China also maximize the efficiency of the overall PV innovation system.

Table 3.2 Solar PV Technologies by Leading Patent Holder Types

Leading Sector	Solar PV Technology
Academia	organic, pervoskite, DSSC, quantum dot, CdTe, GaAs, CZTS, multi-junction
Company	mono-si, poly-si, a-Si, HIT, CIGS, PERC, MWT, IBC

With that being said, there are a few caveats with looking at just the number. Patents, as a means to protect a technology holders' intellectual property, is more complex than its sheer numbers suggests. There are many reasons why an entity wants to file for patents or vice versa.

As a leading Chinese intellectual property lawyer[6] said in an interview "Patent is a numbers game." Both academic and corporate entities want to use patents to protect their intellectual property, to build a large R&D profile to impress investors (in the case of publicly-traded companies) or government grant managers if they want to participate in government-run innovation programs, and to generate economic returns on their investment in R&D.

In the case of some MOST-run innovation programs participants, they are incentivized by the Programs to produce patents. Since the mid-2000s, the STI programs run by MOST started to include criteria related to patent production in the grant agreement, requiring the sponsored projects to produce certain number of patents in order to pass the project evaluation. A special patent-related fund is usually included in the general grant funding in order to provide the financial resource needed in the patent application process. The same is true for many R&D programs sponsored by MOST's local counterparts. For instance, in Shanghai, under the Rules on Patent Sponsorship stipulated on July 1, 2012, any applicants with a Shanghai address is eligible under the patent sponsorship program where 80% of the application fee, 100% of substantive review fee and 80% of the second and third year annual fee will be waived.

[6] Interviewee #111

Nevertheless, there are also reasons why entities want to be prudent about obtaining patents. The CTO of a large Chinese PV manufacturer breaks down the corporate perspective on patenting during an interview.[7] According to him patenting is a strategic decision, which means not all inventions are suitable for patents. Whether to patent a technology or not depends on the company's strategic position on this technology relative to its competitors. If a company decides to patent a technology, the moment the patent is granted that technology becomes public information, and the company's economic rights over it depends on patent law enforcement. If the company has little confidence in a country's patent enforcement regime, it could end up deciding not to file for patents. If a technology is deemed as truly crucial to a company's competitiveness, then it will be treated as proprietary information and patenting is off the table. Sometimes, companies would even pre-empt its competitors from patenting a technology by putting the knowledge related to that technology into the public domain (e.g. publish paper). Finally, from an economic perspective, companies need to decide whether it makes sense to obtain a patent, the cost of which does not only entail the initial application fee but also the renewable fee that occurs annually. The fact of the PV manufacturing industry is that the profit margin is low and there may not be enough financial resources to spend on filing and maintaining a large number of patents.

3.4.2.2. Patent Quality as An Indicator of Innovation

One needs to be cautious when making inference about innovation using one single indicator. Both laboratory cell efficiency and patent numbers measure certain aspect of innovation. For the latter, it provides a sense about how active the innovation players are as seen through their patent behavior. But the numbers along say nothing about the quality of the patents. If both the quantity and quality of the patents can be measured in objective ways, then concrete conclusions can be drawn regarding how

[7] Interviewee #53

innovative the Chinese patent system is. However, patent quality is very difficult to assess. Players from different sectors prefer different measures. The most obvious approach to evaluate the value of a patent is to look at the licensing data (Geuna & Nesta, 2006; Meurer & Bessen, 2005). If a patent is licensed by other entities, it is valuable. However, the opposite is not true, which is to say if a patent does not get licensed, it does not mean it is not valuable. A patent could be simply too ahead of its time to be utilized, or it could be in a niche area where does not see a lot of commercialization activities. As a result, licensing data is only a partial indication of patent quality.

Academics and legal professionals also often use forward and backward citations as an indicator. If a patent is cited by a large number of other patents in their claims, it indicates that the original patent is valuable because it paved the way for later research (Lanjouw & Schankerman, 2004). However, citation analysis favors basic science-oriented patents over applied science and engineering-oriented patents. Legal professionals judge patents based on how well crafted their legal claims are. An interview with a leading patent lawyer based in both China and the U.S. revealed that a good patent should have a broad claim that allows it to cover as much ground as possible but in the meantime also be specific about its uniqueness so that it can pass the patent evaluation.[8] A fourth way to evaluate patent quality is to use lapse rate. Patent lapse rate measures the percentage of patents that did not get renewed. A patent lapses when its holder, for various reasons, fails to pay the annual maintenance fee. Patent holders usually do not allow their high quality valuable patents lapse. However, when they do let their patents lapse, it indicates a drop of patent holders' confidence in the value of their patents, which infers lower patent quality. Therefore, the lapse rate can be used to indicate the overall quality of a collection of patents. Although financial resource constrain may also affect an entity's decision to maintain its patents, however, for truly valuable patents, the patent holders are more likely than not to maintain them.

[8] Interviewee #112

Researchers have applied this lapse rate as a measure patent quality and found it to be effective in evaluating the quality of a collection of patents (Griliches, 1990; Hall & Harhoff, 2012; Schankerman & Pakes, 1985). This study uses lapse rate to evaluate patent quality, for two reasons. First, patent lapses rate can be calculated using the same data from China SIPO, whereas forward and backward citation data and licensing data are not available. Second, all patent quality evaluation methods have their pros and cons, yet the simplicity and straightforwardness offered by the lapse rate approach outweigh its drawbacks.

Table 3.3 compares the overall lapse rate by technology among solar PV-related patents in China (both patents held by Chinese and non-Chinese players) to the lapse rates of Chinese patents. Among all 16 types PV technologies, Chinese patents demonstrate statistically higher lapse rate than the foreign patents in six technologies: organic, pervoskite, CIGS, DSSC, CdTe, and quantum dot, and the differences in lapse rate range from 4.2 percentage points to 7.8 percentage points. For CTZS, and MWT technology, all patents filed by Chinese and foreign entities still remain in force. For 8 technologies – HIT, GaAs, PERC, a-Si, Poly-si, Mono-Si, multi-junction, and IBC – Chinese patents have statically lower lapse rate, although the differences between the two groups are much smaller, ranging from 1.3% to 6.0%, except for IBC.

Two one-way paired t-tests are carried out to test if the differences between the Chinese and foreign lapse rates are statistically significant. The results show that both differences are significant. This means that depending the technology at focus, Chinese patents' quality is uneven across technologies. They have higher quality in certain technologies while lag behind their foreign competitors in others.

Table 3.3 Lapse Rates by Technology*

Technology	Foreign lapse Rate	Chinese lapse rate	Lapse rate difference	Overall Main Patent Holder Type	Main Patent holder Type in China
Solar PV Technologies with Higher Chinese Patent Lapse Rate					
Organic	7.4%	15.2%	7.8%	Company	Academia
DSSC	10.3%	18.1%	7.8%	Academia	Academia
Quantum Dot	12.2%	19.8%	7.6%	Academia	Academia
CIGS	6.5%	13.8%	7.3%	Academia	Company
Perovskite	15.4%	20.0%	4.6%	Company	Academia
CdTe	10.6%	14.8%	4.2%	Company	Academia
One-way paired t-test	P= 0.0001. Chinese lapse rate is significantly higher than the overall lapse rate 0.05 statistical level				
Solar PV Technologies with the same Overall and Chinese Patent Lapse Rate					
CTZS	0.0%	0.0%	0.0%	Academia	Academia
MWT	0.0%	0.0%	0.0%	Company	Company
Solar PV Technologies with Lower Chinese Patent Lapse Rate					
GaAs	9.1%	7.8%	-1.3%	Company	Academia
PERC	7.7%	6.0%	-1.7%	Company	Company
HIT	18.9%	16.0%	-2.9%	Company	Company
Mono-Si	14.4%	10.0%	-4.4%	Company	Company
A-Si	16.7%	11.6%	-5.1%	Company	Company
Multi-junction	13.2%	8.0%	-5.2%	Company	Academia
Poly-Si	17.0%	11.0%	-6.0%	Company	Company
IBC	12.0%	0.0%	-12.0%	Company	Company
One-way paired t-test	P= 0.0024. Chinese lapse rate is significantly lower than foreign lapse rate the 0.05 significance level				

*Data on patent lapse counts by technology collected by Evalueserve http://www.evalueserve.com/ as part of Stanford University China Project.

It is interesting to notice that academics are the majority holder of five out of the six types of technology that China has higher lapse rate, with perovskite being the only one exception, whereas the profile of the foreign group shows that academics are only the majority patent holder in 3 technologies –DSSC, quantum dot, and CIGS. In contrast, among the 8 technologies with lower Chinese lapse rate, only two have the academics as majority patent holders – GaAs and multi-junction. The fact that academia-led technology areas tend to have higher patent lapse rates in China suggests that Chinese academics file for more patents than they can or are willing to realistically maintain, and there is a greater variation in quality among their patents. In fact, the patent filing decisions among Chines academics are influenced by policies. As mentioned earlier, MOST-run innovation programs such as the 973 and 863 Program require certain number of patents produced as a result of the government-sponsored innovation project, and a portion of the grant funding is dedicated to cover patent application-related expenses. With the requirement and financial support, Chinese academics are eager to file for patents, which explains the large number of patents obtained by them. According to Chinese solar PV scientists who were involved in multiple 973 and 863 projects, even though there had been a number of high quality patents produced through the projects that they were involved in, some patents they filed were not superb and if it were not for the purpose of meeting the requirement they might not filed those patents[9]. Plus, academics in China often are agnostic about patents, when they occur no cost to themselves in filing for patents, they usually will as well do it.

However, there is one catch with the MOST patent-related funding: it covers patent application fee, but does not always cover the renewal fee. Depending on the cases, sometimes, part of the renewal fees in the first two years are covered by MOST grants, while some other times, patent applicants are responsible for the renewal fees. So even if it is free from the academics' perspective to file for patents, once their patents are

[9] Interviewee #52, #93

granted, they will need to deal either partially or completely pay for the renewal fees. For those who filed the patents just to meet the MOST requirements or to take advantage of the patent application subsidy rather than genuinely wanted to protect their patent-worthy intellectual property, they are unlikely to keep up with the renewal, which explains the high lapse rate.

3.4.3. Publications – Measure the Innovation Output

This study conducts a meta-analysis on solar PV related publication. A bibliometric analysis conducted by Chinese Academy of Science and Technology for Development (CASTED) shows that by august 2014, Chinese journals have published 16,914 solar PV-related articles; 7,587 master and the doctoral theses were devoted to solar PV research; 3,681 academic conference papers discussed solar PV technologies (CASTED, 2014). The growth rates in all three categories are high in China. However, despite the fast growth, the absolute number of Chinese publications is small compared to 82,217 English language journal publications and 22,983 international conference papers. Du et. al looked at solar energy (including but not limited to solar PV) literatures between 1992 and 2011 and concluded that China is second to the U.S. in terms of total number of publications, accounting for 9.79% of the world total solar energy related publications (Du, Wei, Brown, Wang, & Shi, 2012). China has the fastest publication growth rate, especially in the post-2007 period, a trend similar to what was discovered about patents. CAS and Shanghai Jiaotong university are the third and forth most productive institutes in the world.

The publication patterns show that China is coming from behind and catching up to the world's leading countries in terms of scientific discovery in the solar technology realm. The fast publication growth rate is an indicator that China is making a big effort to improve its ability to conduct scientific innovation and judging from the publication numbers, the effort is paying off.

3.4.4. Summary of Findings – Output in the Chinese Solar PV Innovation System

Up until this point, this study uses Chinese and the world record solar cell efficiencies, quantity and quality of solar PV patents, and the quantity and quality of solar PV publications as indicators of outputs of the Chinese solar PV innovation system to answer research question 1a. It is noticed that the answer to the question is nuanced. China is clearly making efforts to improve its innovation capacity, although depending on the choice of indicator and the technology at focus the progress is uneven.

Using cell efficiencies of five types of solar PV technologies across all three generations as an indicator, it is found that China is becoming more and more active in solar cell innovation, suggested by the rising record solar cell efficiencies. For four out of the five technologies, the efficiency gap between China and the world's leading innovators are narrowing, indicating that China is growing its innovation strength at a relatively fast speed. However, CdTe represents technologies where effort to produce innovation progress has been stagnant.

In terms of solar PV related patents, the number of patents granted to Chinese entities in China is increasing dramatically, the trend of the same indicator is mirrored in the U.S., although the absolute volume of patents is much smaller in the latter case. Judging from patent quantity in China, Chinese entities have surpassed their foreign competitors in all sixteen PV technologies except IBC. The large number of Chinese patents and the fast growth rate indicate that solar-PV innovation players in China have increased their effort to create patent-worthy knowledge and products while becoming more aware of the means to protect their intellectual property and enhance their competitiveness.

Nevertheless, the analysis of patent quality using lapse rate as an indicator shows that the quality of Chinese patents is uneven across technologies. In six technologies, Chinese patents have statistically significantly higher lapse rates, meaning lower patent quality, than their foreign counterparts. However, in eight other types of technologies, Chinese patents have statistically higher patent quality than foreign patents obtained in China. In addition, Chinese academics own more solar PV patents than Chinese companies, but they are also more likely to let their patents go lapse. Analysis done by this study found that academics' patent application decisions are made often based on their obligations to meet requirements of government issued-grants rather than an objective evaluation of the quality of their work.

The rising but yet still small number of U.S. patents obtained by Chinese entities shows that although the Chinese are becoming more and more active in seeking to produce high quality patents, their absolute innovation strength is still relatively weak.

Last but not least, the trend in publication is similar to that in solar cell efficiency for HIT and CIGS. China is overcoming a historical gap in knowledge production and is catching up to the world's leading countries in terms of scientific discovery in the solar technology realm. The fast publication growth rate suggests that China strives to improve its ability to conduct scientific innovation, and judging from the publication numbers, the effort is paying off.

Given the noticeable yet uneven innovation progress, this study further asks the question what factors enabled or impeded the advancement of solar PV innovation in China? It turns out three factors really mattered: policy, money and people. The next three sections are going to explore these factors in detail using the TIS framework.

3.5. National Institutions and Their Impact on Solar PV Innovation

Under the TIS framework, there are formal institution and information institutions. Formal institutions refer to rules, laws, regulations, and policies. Informal institutions include culture and social norms (Bergek et al., 2008). In the context of this study, formal institutions in China's solar innovation TIS subsystem include its national vision for solar innovation, FYPs and sub-FYPs that specify innovation topics, goals, and tasks, and a suite of STI programs that carry out the implementation and execution of the innovation tasks. Together, the formal institutions build a structure of the solar innovation ecosystem and provide an environment where innovation actors interact with each other and shape and change the innovation subsystem.

The most important informal institution is China's pragmatic culture, which profoundly influences the structure of the system, the makeup of the actors, and their interactions. This section will unpack the institutions, both formal and informal, to understand how they affect the overall wellbeing of the PV innovation subsystem.

3.5.1. An Evolving National Vision for Solar Innovation Through FYPs

China started to place high priority on developing the solar energy sector since the late 1990s, after realizing its potential in solving the energy and environmental problems. Its long history with central planning makes it that China approaches this development quite methodically. It uses national Five Year Plans (FYPs), the most important social and economic planning tool in the country, to launch grand strategic visions to lend ***legitimacy*** to solar energy and ***influence the direction of search*** of the scientific community. It will then use sector specific sub-FYPs to further set goals and development benchmarks. Interestingly but unsurprisingly, innovation was not the initial focus of China's push for solar; it was the industrialization of the solar panel manufacturing industry that got the attention first. Nevertheless, solar innovation receives increasing regulatory and financial support over time, but the duo-focus of technology R&D and product industrialization permeates the solar innovation policymaking in China as discussed below.

3.5.1.1. The 10th Five Year Plan Period (2001-2005)

China started to form a national strategy for the solar energy starting from its 10th FYP in 2001. In the 10th FYP period, for the first time, China issued a plan specifically for the new and renewable energy industries titled the 10th FYP for the New and

Renewable Energy Industry Development. In this Plan, the then State Economic and Trade Commission, the predecessor of NDRC, laid out a path of market-oriented development. The overarching principle in this plan is to industrialize the new and renewable energy industries, including the solar industry, through economies of scale. For solar PV in particular, the emphasis was placed on scaling up PV cell and panel production as well as developing a robust PV supply chain. Well-defined panel manufacturing and supply chain development goals were proposed in the Plan. It called for a 15 MW annual solar cell manufacturing capacity and a fully-developed PV module supply chain by the end of the planning period. The plan also proposed a 53 MW of cumulative solar PV deployment goal by the end of 2005. As much as the Plan stressed the industrialization of the new and renewable energy industries, it also called for more research innovation in the respective technology areas. It encouraged the private sector to take the lead in innovation, to form collaborations with universities to develop new technologies and then transfer them to commercial production. The plan also proposed to improve China's capacity in solar cell and panel production equipment manufacturing. Technology innovation was mentioned as a measure to improve the competitiveness of the industry but was followed with no substantial details.

Overall, the 10th FYP emphasized industrialization and scaling up the PV manufacturing industry, which goal, as history later shows, was well over-achieved. The market responded to the policy signal with a lot of enthusiasm. A large number of solar PV manufacturing firms emerged in China during this five-year period, many of which later became global solar PV manufacturing leaders such as Suntech, Yingli, Trina. The annual solar module manufacturing capacity was over 500 MW in 2005, 33 times more than the FYP's proposed goal. In essence, the 10th FYP started the solar manufacturing market (***market creation***).

3.5.1.2. The 11th Five Year Plan Period (2006-2010)

In The 11th FYP for Energy Development, the theme of industrialization through economies of scale continued to be the principle of developing the renewable energy industry. More solar PV related details were laid out in the 11th FYP for Renewable Energy Development. The Plan acknowledged the fast growth of the PV manufacturing industry in the last FYP period as well as the lackluster performance of solar PV innovation, and proposed to devote more effort to solving technical issues such as the production of high purity poly-silicon and grid connection of large solar PV farms through R&D. Compared to the 10th FYP, the 11th FYP for Renewable Energy Development put forward specific PV deployment goals: 300 MW of cumulative installed solar capacity and 540 GWh of annual electricity generation by the end of 2010 (***market creation***).

Besides the FYP for renewable energy, the 11th FYP for High Tech Industry Development also shed light on PV technology innovation. This is the first time that solar PV was discussed not as an energy matter, but as a technology research and development issue along with other popular emerging technology areas like IT, biotech, aerospace, and etc. This Plan called for more research in the following solar PV related areas: poly-silicon material production, high-efficiency solar PV and its application in large-scale electricity generation, and building integrated solar PV (BIPV). One similarity between the Renewable Energy Development Plan and the High Tech Industry Development Plan is that they are both stress the importance of economies of scale to the solar PV industry. This emphasis of building a large manufacturing capacity is consistent with the previous FYP. As the CTO of a world's leading Chinese solar PV manufacturer said

"Solar in China is an industry first, a science subject second." [10]

Even though more attention had been given to solar innovation in the 11th FYP cycle, the end goal of innovation was to better serve the manufacturing industry and strengthen its competitiveness. For example, due to the lack of domestic suppliers, China

[10] Interviewee #53

relied heavily on imports for a few key materials and equipment required in solar cell and module manufacturing, such as high purity silicon, EVA, silver paste, fully-automated screen printing machine, etc. Starting from the 11th FYP, MOST designated these areas as "bottleneck issues" to building a globally competitive Chinese PV industry. It started to fund research projects to acquire knowledge on these fronts. The ultimate goal was to build a fully developed domestic supply chain. MOST's effort ***created positive externalities*** that spread from the solar innovation TIS subsystem to the manufacturing subsystem. China's reliance on imports in materials and equipment declined significantly during these 5 years. Domestically produced poly-silicon met 50% of the totally demand in China in 2010, up from only 10% in 2005. The trend is best highlighted by companies like GCL-Poly, which grows from a little known company to today's world's largest producer of PV grade silicon and supply over 90% of Chinese PV industry's demand in 2014. During the same time period, 70% of the tooling demand were met by Chinese equipment providers, a significantly leap from the 2005 situation where almost all Chinese manufacturers used imported tooling (NDRC, 2011). MOST's targeted efforts on solving innovation bottlenecks have allowed the entire solar PV supply chain in China to make progress in overcoming technical barriers.

The 11th FYP period marks the golden age of China's solar PV industry. The manufacturing capacity grew from 500 MW in 2005 to just under 8.7 GW in 2010; more than a third of the global solar panel demand during this five years was met by Chinese producers; seven Chinese solar panel manufacturers became publicly traded companies in the U.S.; Dr. Zhengrong Shi, the founder and then chairman and CEO of Suntech was made the wealthiest person in China in 2006 and was featured on the cover of Fortune magazine in 2008. These facts highlight how vibrant the manufacturing sector was during the 11th FYP period.

While the manufacturing sector made a big splash globally, solar innovation in China stayed low profile. Neither groundbreaking inventions nor breakthrough advancement to existing technologies were made, although steady improvements were achieved in many of the “bottleneck” research areas.

3.5.1.3. The 12th Five Year Plan Period (2011-2015)

China’s planning for solar PV continued to become more nuanced in the 12th FYP period. In additional to being an integral part of the energy development plan, the 12th FYP, for the first time, had not one but two specific plans dedicated to solar PV: The Special Plan for Solar Electricity Generation Technology Development (NDRC, 2010a) and The Special Plan for Solar PV Industry Development (NDRC, 2010b). The former plan aimed to bring more affordable solar electricity to China’s energy mix and the latter plan intents to strengthen China’s advantage in the solar PV manufacturing field. It is worth noticing that both plans acknowledge the role that innovation can play in achieving their respective goals, and the give similar prescriptions for how to approach solar innovation.

Between the two plans, China aimed to ramp up innovation activities along the entire solar PV value chain, including research in the following four areas:

- Materials that are crucial to high-performance PV cell such as high purity silicon, EVA, etc;
- High-performance cell and module
- System integration of solar;
- Tooling needed to in cell and module production.

Table 3.4 shows the innovation topics and specific goals outlined by the two Special Plans. Cell and module as well as system were given a large amount of attention in the plans; each has eight different innovation topics assigned to them. Two topics were identified for materials related research.

Table 3.4 Innovation Topics and Goals Proposed in the 12th FYP Special Plan for Solar Electricity Generation Technology Development

Focus Area	Innovation Topics	Innovation Goals
Materials (2)	New high-efficient, low-emission ways to mass produce poly-silicon	Improve the "modified Siemens process" for mass, low-cost, clean production of silicon; Achieve mass production using the silane method; Explore new low-cost production method.
	Auxiliary materials used in solar PV panel production	Master the techniques to produce the following materials: silver paste; aluminum paste, TPT back sheet material, EVA; and TOC glass substrate for thin-film
Cell and Module (8)	Cell efficiency improvement and/or pilot line production for seven types of solar cell technologies and concentrated solar power	Table 3.5
System (8)	Grid integration of utility-scale solar PV	Master power station designs and grid integration techniques for 100MW level solar-plan grid integration
	Microgrid with solar	Master techniques for micro-grid stability and quality control system.
	High voltage inverter for microgrid	Master the design and production of self-controlled synchronous voltage-source inverter and its application in microgrid operation
	10MW level CPV	
	Large scale solar power grid integration with other renewable sources	Master system design and operation techniques required in grid integration of large scale multi-renewable energy sources
	Silicon-based building-integrated solar PV	Build a BIPV panel production industry and its tooling supply chain
	Distributed CPV	Master 100kW level distributed concentrated solar power technologies and the power electronic technologies required to operate the system
	Solar thermal storage	Improve thermal storage materials; master thermal energy transmission and distribution technologies
Tooling	Required in the above areas	Table 3.5

Technology coverage is also broad and comprehensive in the two Special Plans. They identified specific research areas for all three generations of PV technologies and attached assessable goals to each area. As seen in Table 3.5, for each solar PV technology, there are two sets of goals related to them: the innovation goals and the commercialization goals. The innovation goals include cell-efficiency targets but often times also entails requirement for tooling R&D. To China, the ability to produce tooling needed in solar cell and module manufacturing is crucial if it wants to maintain its status as the manufacturing mogul in the solar industry. Given its significance, China had called for developing an all-encompassing domestic solar PV supply chain with robust tooling manufacturing capacity since the 11^{th} FYP. Although its domestic tooling manufacturing capacity had come a long way, moving from completely relying on foreign equipment to 70% self-efficient, China is aspired to become complete self-sufficient by the end of the 12^{th} FYP cycle, and hence the push for tooling research in the two Special Plans.

The call for tooling R&D also connects the innovation goals with the commercialization goals. The latter appeared hand-in-hand with the former in the Plans. This is yet another evidence showing the practical innovation culture in China where innovation does not exist in isolation but rather serves a purpose for the industrialization in the country. The commercialization goals outlined in the Plans aim to transfer the innovation outcomes to factory floor by requiring pilot production lines or mass production lines to be built by the end of the planning cycle (Table 3.5). This ***influenced*** the scientific community's ***direction of search***. Instead of creating prototype solar cells, MOST-sponsored program are often required to produce pilot production line that can manufacture the prototype cells. In addition, production cost targets were also specified for CdTe, a-Si, and tandem solar cell technologies. Overall, the integration of the two sets of goals illustrates that solar PV innovation as laid out in the 12^{th} FYP went beyond just creating high performance solar cells; it also included mastering the science and technological knowledge involved in the entire production cycle and discovering new approaches to lower the production cost.

Table 3.5 Solar Technology Innovation and Commercialization Goals in the 12^{th} FYP

Technology	Innovation Goals	Commercialization Goals
Mono-crystalline silicon (mono-Si)	19% and above average commercial efficiency	Domestic supply of key tooling equipment; 100 MW production capacity of high-efficient silicon solar PV
Poly-crystalline silicon (poly-Si)	20% and above average commercial efficiency	
CIGS	Master key CIGS tooling design and manufacturing techniques; electrochemical deposition method	5MW roll-to-roll flexible substrate CIGS production line; MW level flexible substrate CIGSS pilot production line
Cadmium Telluride (CdTe)	10% and above average commercial efficiency; 100% self-designed and self-produced tooling for 30MW production line	30 MW CdTe production line; CdTe turnkey solutions; 5 RMB/W ($0.8/W) production cost or lower
Amorphous silicon (a-Si)	10% and above average commercial efficiency; 100% self-designed and self-produced tooling for 40 MW production line	1 MW roll-to-roll flexible subtracted a-Si pilot production line; 40 MW production line; turnkey solutions; 5 RMB/W ($0.8/W) production cost or lower
Dye-sensitized Solar Cell (DSSC)	8% and above average commercial efficiency; master materials and tooling required in mass production	5MW level production line
Heterstructure Intrinsic Thin-layer (HIT)	18.5% pilot line efficiency	2MW capacity pilot production line
A-Si/μc-Si tandem solar cell	8% and above average commercial efficiency; a-Si materials; Tooling for mass production	50MW production line; 5 RMB/W ($0.8/W) production cost or lower
GaInP/GaInAs/Ge multi-junction	Master multi-junction cell design and production techniques	5MW pilot production line
Concentrated solar PV (CPV)	35% commercial efficiency; master CPV power plant control system and inverter design	5MW capacity pilot production line

Compared to previous FYPs, the two plans issued in the 12th FYP period are more nuanced and articulated in terms of specifying research areas and setting measurable research goals. Table 3.6 summarizes the evolution of solar innovation planning over the past 3 FYPs. The trend is clear that the solar energy receives more policy attention overtime. It started as a manufacturing industry before and during the 10th FYP, but has since evolved to integrate more components of science and technology innovation. Although the emphasis on product commercialization and the industrialization of the entire supply chain has been consistent and remained strong, the rising importance of innovation is also clear.

Table 3.6 Solar Innovation Planning in the 10th, 11th, and 12th FYP

	Specific Plan for Solar PV	Emphasis on PV Innovation	Emphasis on PV Industrialization
10th FYP (2001-2005)	No. 10th FYP for the New and Renewable Energy Industry Development.	Briefly.	Heavily. Emphasize economies of scale.
11th FYP (2006-2010)	Yes and No. No: No PV specific sub plans. Yes: 2 sub-FYPs have specific sections dedicated to solar PV: 11th FYP for High Tech Industry Development; 11th FYP for Renewable Energy Development	Good amount. The 11th FYP for High Tech Industry Development. Identify research areas: poly-si production, high-efficiency solar cells and their application; BIPV	Heavily. The 11th FYP for Renewable Energy Development. Emphasize economies of scale and full supply chain development.
12th FYP (2011-2015)	Yes. Two PV-specific plans: Special Plan for Solar Electricity Generation Technology Development; Special Plan for Solar PV Industry Development	Heavily, with well identified research needs and assessable goals. The 12th FYP Special Plan for Solar Electricity Generation Technology Development.	Heavily, with aims to integrate with innovation. The 12th FYP Special Plan for Solar PV Industry Development.

Despites its evolution, China's PV innovation strategy does not explicitly place high priority on advancing the scientific frontier and producing cutting-edge technologies. As illustrated above, focuses have been placed on two types of actives: the activities that allow China to tackle the bottleneck issues, which often entails achieving the mastery of certain techniques rather than making the best of their kinds; and the activities that would improve China's competitive advantage along the entire solar PV manufacturing value chain. This practical-approach is proven to be a double-bladed sword. On the one hand, it does allow China to achieve an unmatchable manufacturing scale. However, on the other hand, the industry-oriented innovation approach has impeded Chinese researchers from conducting long-term, in-depth, future-oriented research that are unlikely to see immediate market payback. The tradeoff to the self-sufficiency-driven industrialization-oriented research is the lack of originality in China's own research agenda and the absence of scientific and technological breakthroughs. Chinese solar community is becoming more and more aware of the drawbacks. Plenty of criticism about its approach to innovation had been heard by MOST, which to certain extent sow the seeds of the upcoming MOST reform.

3.5.2. Science, Technology and Innovation (STI) Programs

MOST administers some of the most impactful science, technology and innovation programs in China, with the exception of NSFC, which is an independent entity. Individually, each program occupies a niche in the technology development cycle with a certain level of overlap with its adjacent programs by design. Collectively, they cover the entire technology research, development, demonstration and deployment (RDD&D) spectrum. From the most basic research to produce commercialization, there are the NSFC Grant Program (independent to MOST), the National Basic Research Program (also known as the 973 Program), the National High Tech R&D Program (also known as the 863 Program), the State Key Laboratory system (SKL), the National

Science and Technology Infrastructure Program (the Infrastructure Program), and the China Torch Program. According to the specific technology development stage that each program is designed to target, financial resources are allocated through the programs to fund specific R&D projects carried out by innovation players in universities, research institutes and private companies. The size of the financial support and the preferred types of innovation players vary from program to program.

The remaining part of this section provides a close look at these programs and how they relate to solar PV innovation in China.

3.5.2.1. NSFC

Similar to the National Science Foundation (NSF) in the United States, the National Natural Science Foundation of China (NSFC), supports early stage, basic and novel research conducted in universities and research institutes. Public available record on NSFC can be traced back to 2000. CdTe and poly-crystalline silicon are the first two solar technologies receiving NSFC funding. No particular reasons as to why these two technologies were first selected. NSFC's investment in the early 2000s was small and was not consistently provided to any type of PV technology. For CdTe, it did not see the second NSFC grant until 2010; and there is a four year gap between the first and the second NSFC grant to crystalline silicon solar PV. Appendix F details NSFC's investment across the technology spectrum.

Starting from 2007, NSFC broadened its technology choice and began to consistently invest in a portfolio of solar PV technologies, including mono-Si, poly-Si, and a-Si solar PV, amorphous silicon PV, various types of thin film PV technology such as Cadmium Telluride (CdTe), Copper indium gallium selenide (CIGS), and etc., as well as emerging technologies like pervoskite, organic, dye-sensitized solar PV.

Grants awarded by NSF are typically around $75,000 to $100,000. Because of the early-stage nature of NSFC research that NSFC supports, individual researchers can apply on their own without having to form partnership with fellow researchers or companies.

3.5.2.2. The 973 and the 863 Program

The National Basic Research Program, also known as the 973 Program, and the National High Tech R&D Program, i.e. the 863 Program, are two flagship innovation programs under MOST.

Established in March 1997 (hence, 973) under MOST Office of Basic Research, the 973 Program aims to support large-scale basic research projects. Compared to the exploratory nature of NSFC, the 973 Program requires projects to have proven concepts and they must show that their results will have significant impact on China's society and national economy. In other word, NSFC projects can be out of pure scientific curiosity, but 973 projects must have a social mission. The Program is also forward looking, aiming to lay the ground for the so-called "technologies of tomorrow".

Since its inception in March 1986, the 863 Program focuses on R&D areas that are further along down the technology maturity curve. It mainly supports high-tech projects that have demonstrated great potential for commercialization but still need to address a few key science and technological issues. Private sector players play an increasingly important role in the 863 Program because they have a better sense about the market potentials of technologies and where innovations are needed in order to bring the technologies to market. Starting from the 11th FYP, MOST officially encourages companies and other private sector players to participate in the 863 Program. Research proposals that are jointly developed by private companies and academics receive priorities in the grant application process. This change ***mobilized*** private sector actors to more actively take part in the innovation.

3.5.2.3. State Key Lab System and State Engineering and Technology Research Center System

The State Key Lab (SKL) system and the State Engineering and Technology Research Center (SETRC) system are made of laboratories and research centers from universities, research institutes and companies, which have demonstrated strong research capacity in certain science or engineering areas that are deemed as important to Chinese society and national economy. Once acknowledged as a SKL or a SETRC, labs and research centers will receive long term funding from MOST. One SKL or SETRC term is usually 5 years, but labs and centers with good performance are usually renewed for a second, or even a third term. This is designed to ensure some level of constant public finance support to major research groups and enable them to build long-term research strength. The SKL and SETRC system also give more freedom to research groups to select their own topics of investigation and partners to collaborate with. The financial support coming from the SKL and SETRC System is mainly used for the overall building and operation of a lab or a research center like purchasing lab equipment, hiring researchers, and paying for operation costs, etc. No string is attached to any particular research projects. The idea is to release researchers from the worry for money so that they can dedicate their energy to their research.

There are two solar-related SKLs: the State Key Laboratory of Photovoltaic Materials and Technology at Yingli and the State Key Laboratory of PV Science and Technology at Trina. Exhibit 1 and 2 in Appendix B give an overview of these two SKLs.

Three solar-related SETRCs involve both academics and private sector players. LDK Solar is home to the State Photovoltaic Engineering and Technology Research Center. The 48th Research Institute of China Electronic Technology Group Corporation houses the State PV Tooling Engineering and Technology Research Center. Finally, the State Photo-electronic Crystalline Material Engineering and Technology Research Center is located in the Chinese Academy of Sciences' Material Structure Research Institute in Fujian.

Besides the central government level labs and research centers, provincial and local level innovation programs support an even larger number of projects in China albeit the quality of the projects may be lower than the top tier national projects. According to the research of China Renewable Energy Industry Association (CREIA), there are 2 provincial level key labs in Liaoning and Henan province and 6 provincial level ERTCs located in Jiansu province, Hubei province, and Beijing (Table 3.10) (CREIA, 2014).

3.5.2.4. National Science and Technology Infrastructure Program

The Infrastructure Program is a demand-oriented program in the sense that it gauges its R&D support according to the need of the economy and key national infrastructure projects, as well as industries' demands for new tooling. Technologies covered by the Program are usually relatively mature and have shown potentials to have significant social impacts. The Program's goal is to connect the technologies with the markets that they can serve, which include both the consumer market and the pubic sector. For example, China Silicon Corporation has received support from the Infrastructure Program for 5 different projects related to technology and tooling used in mass production of high purity silicon.

Starting from the 11th YFP (2006-2010) the Program encourages private enterprises to play the leading role in formulating projects that have a clear focus on products development and their commercialization. Unlike the 863 Program, which despite the application-oriented focus, relies primarily on public finance to fund R&D projects, the Infrastructure Program sees its investment into industrialization and commercialization projects as an invitation to private enterprises for them to devote more of their own resources into R&D, typically no less than 50% of the total project budget. It has been doing so through a suite of new financing mechanisms such as subsidized-interest R&D loans, revolving loan fund, and allowing private venture capital to invest in technology R&D.

3.5.2.5. China Torch Program.

The Torch Program is the most market-oriented program of all. It champions the commercialization, industrialization, and internationalization of R&D products by supporting building high tech industrial parks, developing technology service industries, providing R&D financing to innovative SMEs, and facilitating international collaboration. The goal of the Program is to *facilitate,* rather than *direct*, the market-oriented R&D activities. As a result, much of its effort has been focusing on building an environment for innovation and commercialization and solving the auxiliary needs such as information exchange, personnel training and etc.

The recipients of the Torch Programs are almost all private sector players: high and new tech companies, especially SMEs, industrial parks with a high tech focus, and technology service companies.

3.5.2.6. Thousand-Talent Program

The Thousand-Talent Program is a research expert recruitment program started in 2008 by more than 20 central government agencies. Its mission is to ***mobilize human resource*** by recruiting top-notch research experts from all over the world. The establishment of this Program reflects the idea that people are just as important to China's national innovation system as financial resources. Yet, for a long time, China has been leveraging the latter while overlooking the importance of the former. With the Thousand-Talent Program, the emphasis on attracting and retaining research talents have been made it clear. By the end of May 2014, the Program has recruited 4180 research experts from overseas and majority of them are foreign-trained native Chinese researchers. [11]

[11] Interviewee #106, #107

The Thousand-Talent Program evolves over time. Before 2012, the Program recruitees were placed mostly in R&D positions at Chinese universities and research institutes. Since 2012, the Program increased its effort to attract experts who are the intellectual property owners of technologies and are looking for opportunities to start their own business. In both pure research and business-oriented recruit cases, the recuritees are provided with an incentive package that includes a job post at a leading Chinese research institute or company, personal financial reward (usually at one to five million RMB per year level), a research budget, and administrative supports for research and business development. People who are recruited by the national Thousand-Talent Program usually also receive local incentives, which include subsidized or free housing, matching research budge, and etc. In the solar energy field, the founder of Suntech, Dr. Zhengrong Shi; the chairman and CEO of Canadian Solar Dr. Xiaohua Qu; China's leading researcher in HIT solar cell, Dr. Zhengxin Liu are all recruited by the Program.

The evolution of the program is also manifested in the age cohort. The program used to focusing on attracting well-established senior scholars, but soon they found out that these senior scholars were more likely to take part-time positions and spilt their time between China and their overseas bases than permanently relocate back to China because of their concern for the work and education opportunities for their spouses and children. In order to attract scholars that are more committed to building their career in China, the Program shifted its focus to young and mid-age overseas scholars who are at the early stage of their career and are more open to the idea of moving their entire families back to China. This change in recruiting target resulted in more full-time positions being taken by overseas returnees.

The Thousand-Talent Program has been proven to be important to China's growing innovation strength for the following reasons.

First, they are trained overseas with rigorous theoretical and methodological skills. When they return to China to teach Chinese students, they introduce the same rigorous training to China. By ***diffusing knowledge*** and methodologies, they help improve the quality of China's higher education in science and engineering fields.

Second, the recuritees are all well-vetted top tier researchers who are at the forefront of their respective R&D field. They stay up to date with the latest research and have an acute sense about where the research is going. Therefore, they are likely to discover the "next big thing", rather than only playing the catch up game.

Third, trained overseas expanded Chinese science community's network to a global level. They take their overseas networks with them to China, and sever as bridges that link Chinese research community more closely with overseas communities, allowing the former to be further integrated into the global research network. ***Knowledge development and diffusions*** happen more easily and frequently when scientists talk to each other.

Lastly, overseas returnees are fluent in English as well as research collaboration international. They help to close the communication gap between the native Chinese research community and the broader international research community. Academic communication is crucial to Chinese innovation.

The Thousand-Talent Program is not the only global R&D expert recruiting effort in China. The Yangtze Scholar Program under the Ministry of Education, and the Hundred-Talent Program at CAS are other examples of central-government level programs. All Chinese provinces and many local governments also established their own research talent recruitment programs.

Driving mechanism 3.1: Effort to recruit overseas top tier Chinese researchers back to China has significantly narrow the knowledge, scientific methodology, and communication gaps between China and the world innovation leaders, broadened the network and improved the innovation strength of Chinese solar PV research community.

3.5.3. Informal Institution: the practical attitude towards innovation

China holds a pragmatic (practical) view towards innovation. Unlike the West which approaches solar PV innovation as a constant effort to invent new technologies and to set new efficiency records for existing technologies, China treats innovation as everything that brings improvement to the performance and production of a PV technology. This philosophical difference in understanding innovation between China and West manifests in the following three ways.

First and foremost, according to the Chinese, innovation does not equal to invention. Although the pursuit of original ideas and new technologies are encouraged in China, research and development that focuses on improving the efficiency and performance of existing technologies has also been an integral part of the Chinese innovation system. This is especially germane given the fact that China has a large historical knowledge gap to overcome in order to stand side by side with its western peers. For instance, China had to rebuild its education and R&D infrastructure in the late 1970s and early 1980s after 10 years of stalling, if not regressing, in education and research due to the Cultural Revolution. Solar cell technologies came a long way worldwide while China was in a standstill.

Given the historical gap, China's solar technology innovation campaign started in the late 1990s has been focusing on catching up to the West. Chinese researchers spend much of their efforts in mastering technologies developed by western scientists. The first generation of post-cultural revolution solar cell scientists in China started the field almost from scratch since there was little knowledge to draw from. Their main goal was o undo the damage inflected by Cultural Revolution and to catch up to the leaders in the filed as much as possible. Therefore, any small improvement on solar cell efficiency was seen as a hard-fought progress, even if they came a few decades later than the initial progress made by western scientists. The fact that solar technology innovation in China has been a catch-up game for a long time means that Chinese researchers do not necessarily see their mission as to create the highest-efficiency cell or invent a new cell structure. Rather, they are driven to close the gap between China and the West. During one interview with a current leading Chinese solar cell scientist, the oversea-trained scientist stated the goal of his research group as “not necessarily to develop new world efficiency records, but to ensure China has the ability to mass produce HIT and CIGS (two technologies that were invented in the West).”[12] This mindset partly explains why none of the world record cell efficiencies was set by China until very recently. Nevertheless, Chinese researchers have managed to improve solar cell efficiencies steadily over time albeit the lack of ambition to be the leader of solar cell research.

The second informal institutional belief that affects China’s approach to solar innovation is its treatment of innovation as an academic-industry continuum, which encompasses not only scientific research conducted by scientists in labs but also process innovation developed by engineers and even production line workers. As seen earlier, solar energy in China was developed as an industry first, a research subject second. Because the PV manufacturing industry has a head start, it has stronger influence on the researcher community compared to its western peers. To keep up with PV technology advancements, large Chinese solar PV manufacturing firms invest in their own R&D departments as well as in collaborations with domestic and foreign universities and research institutes. For examples: Trina and Yingli each has a State Key Lab jointly established with MOST (see Appendix B, Exhibit 1 and 2). In addition, Trina collaborates with CAS, Yingli and Canadian Solar collaborates with ECN in Netherland, and Suntech collaborated with Fraunhofer in Germany. The list goes on. Through both in-house and joint research, Chinese PV manufacturers lead R&D in a pragmatic direction because they are not only interested in the physics of solar cell technologies, but also practical matters such as manufacturability and production cost. As a result, their academic R&D partners’ are influenced by such pragmatic demand in a way that they

[12] Interviewee #59

extend their research agenda beyond just answering intellectually interesting questions but also consider the practicality and the commercializability of their R&D product. This sentiment is reflected in many interviews we conducted with Chinese solar PV scientists, who often stressed the importance of transferability between their lab R&D products and mass production.[13]

Last but not least, the consideration for cost is so deeply rooted in Chinese solar PV industry that it permanents the entire solar PV value chain, including the innovation system. Scientific and technological merits of solar cells are only one side of the coin; innovations that lead to production cost reduction are just as germane as the science and technology underpinnings. Besides manufacturers' drive for process innovation, Chinese scientists and engineers have learned to be cost-sensitive at their work. Because innovation is seen as an academia-industry continuum in China, the manufacturing industry's desire to control cost is very visible to the solar innovation system in China. In one conversation with a renowned Chinese PV scientist, we made an observation that there had not been a single cell efficiency record set by Chinese entities (until November 2014). In response, he pointed out that all the record-efficiency cells are either technologically too complex or economically too expensive to produce, whereas the cell his research team had been working on was designed with mass-production and low-cost in mind from the very beginning, so even if he does not have a world record under his belt, he was hopeful that he will see his product being applied in the real world. [14]

China's pragmatic approach towards innovation has its big downside. To certain extent, the low-cost easy-to-make nature of process innovation overshadows the importance of scientific innovation because the former is easier to do and it directly helps with cost reduction whereas the latter not only has a longer payback period it sometimes even goes against the short term cost-containment goal. Too much emphasis on low-cost

[13] Interviewee #45, #52, #59
[14] Interviewee #45

would render the innovation shortsighted. It provides reverse incentive for researchers to not engage in long-term scientific investigation but only chase short-term marginal improvement.

Although the catch-up strategy seems to work for China in the past, but the danger of such strategy is that it makes the scientific community comfortable with following the world leaders' footsteps rather than attempting to be the leaders themselves. This strategy may bring the Chinese PV industry practical economic benefits in the short term, but in a scenario where disruptive technology emerges, Chinese PV industry will soon find itself losing its market dominance.

Blocking mechanism 3.1: The pragmatic culture in China caused the solar PV innovation subsystem to focus on short-term commercial success at the cost of long-term scientific innovation. It also resulted in a "catch-up" mindset, providing a reverse incentive for the subsystem to achieve breakthroughs.

3.6. Innovation Investments and Their Impact on Solar PV Innovation

3.6.1. An Overview of China's Innovation Spending

Research and development spending in China totaled at $190 billion (1.18 trillion RMB) in 2013, equal to 2.08% of the annual GDP, representing a slight improvement from the 1.98% in 2012. Over three quarters of the total national spending was used in corporation-led R&D activities, which is consistent with the latest policy guidance to let private sector players become the main agent of innovation. Research institutes and universities accounted for another 15% and 7.2% of the R&D spending. Public finance was the largest source of R&D investment; it totaled at about $100 billion (¥ 618.5 billion), representing over 52% of the total national R&D spending, among which 44% came from central government's budget and the remaining was from provincial and local government budge. Public R&D finance at all government levels added up to 4.41% of the total government budget of 2013 (Ministry of Science and Technology of China, 2014).

Solar innovation is part of the China's overall national innovation system. The system has a multi-layered innovation funding mechanism that provides both public finance and private investment to solar innovation players. However, tracing the exact amount of solar innovation investment has been proven to be a daunting task given the limited data availability and low transparency. In fact, difficulties with data availability are a recurring theme in this research, and the frustration with data is shared by many researchers, who work on China-related issues.

3.6.2. Data Issues: You cannot manage what you cannot measure.

This study is aspired to track and analyze the public and private R&D investment into the three generations of solar PV technologies in China. The idea is that the allocation of financial resources reveals the government's and the companies' innovation strategy. By tracing the solar PV R&D investment over time and across the technology spectrum, one can understand the revealed technology preference of the public and private entities in China. The investment pattern can be put side by side to the official innovation rhetoric to assess the implementation of the policies. It can also be evaluated against the innovation outcome in order to understand the effectiveness and the efficiency of the innovation programs. Results of these policy study exercises can in term inform decisionmakers about the success or failure of the past programs and allow them to improve the quality of their policy design.

However, good quality R&D investment data is extremely hard to get in China. Ideally, time series data on public and private R&D expenditures across three generations of PV technology would allow this study to carry out the above-mentioned policy evaluation tasks. However, there is no public database that includes information that is nearly as comprehensive as desired, except for the NSFC. For programs like the 973 and

863 Program, the best public available data is the sporadically released grant approval announcements, but the lack of continuity makes it impossible to tease out the investment pattern over a long period of time. No public data regarding the Infrastructure Program and the China Torch Program can be found.

Poor information transparency and lack of data granularity represent a huge challenge to this study because in order to measure the innovation progress in China and understand the role played by the STI programs in enabling the progress, both historical and current data at the sub-technology level are needed. To make things even worse, data issue in China runs deeper than non-transparency and low data quality. There is real fear among the research community in China that there has not been a good data collection infrastructure and management system in place to ensure the granular data needed for program evaluation are properly collected. As one researcher said during an interview "It's more likely than you think that even MOST itself does not know how money has been spent." [15] This may be a particularly pessimistic view, but it is not very far from truth for the pre-2000 era when data collection and management infrastructure practically did not exist. The historical data gap is impossible to remove, which means policy lessons from those year could never be learned.

The under developed data collection and management system cannot support the need for policy evaluation and resource management. In particular, this study does not only face obstacles related to data availability but also data quality. The available data are often aggregated at the technology family level, like renewable energy, without being broken into specific technologies such as solar, not to mention sub-technologies such as HIT, CIGS, etc. In addition, data found in government reports and announcements usually cannot be fact-checked because the data behind them are not publicly available.

Blocking mechanism 3.2: Ineffective data collection system and poor data transparency make it extremely difficult to evaluate the effectiveness and efficiency

[15] Interviewee #6

of the innovation system. It prohibits policymakers from making informed decisions.

Problems with data availability in China stem from the country's lack of transparency and accountability in its governance culture. Government officials are rarely held accountable to their decisions. In fact, the public's demand for accountability is low historically. It puts no real urgency on improving government transparency. However, as China continues to integrate into the greater international society, western democratic values have made inroads into China. The country sees a rise in popular demand for government accountability and transparency in recent years. First of all, the public wants to know how their tax money is spent, which puts pressure on the government to disclose more information on public spending.

Although the popular demand for accountability in theory should push the government towards a more open and transparent model, but the distrust between the public and the government runs deeper than the latter is willing to admit. As the public becoming increasingly critical about the information they received from propaganda-sounding government reports, they demand independent sources for information and ask for more investigated reporting from the media to expose public sector corruption and government officials' lack of accountability. The ongoing anti-corruption campaign is the government's response to the public sentiment. It has brought lots of cases of imprudent use of taxpayers' money to light. But one unintended consequence of the nation-wide campaign is that government agencies and their officials, in wake of the increasing social scrutiny, become more and more cautious about data release, especially financial data, because of the fear of being investigated against using the same data they gave out. The concern that every bit of information could be used to create a "gotcha" moment makes it not easier but harder to obtain information. Stanford research team experiences this difficulty first-hand. As a foreign academic institute affiliated team, the Stanford team often met with questions about the motive of this research as the beginning of a conversation with government and company officials. Even though the intention of this project is academic and benign, the team still met a good amount of polite rejections to its inquiry because of the distrust of foreign entities by Chinese government and companies. Sometimes, “rules” are quoted as the reason to not give out information, although the team was never able to verify whether such rules against data release to outside entities ever exist.

Despite the difficulties described above, the author found most of the Chinese government officials, company executives, and academics easy to talk to and very open to answer questions and discuss issues. In general, Chinese sources are happy to offer the official rhetoric and their interpretation of them. They are helpful in contextualizing issues. When it comes to answering questions about R&D investment, Chinese sources are helpful in terms of offering their personal knowledge, but they either do not have access to the comprehensive data or are reluctant to provide the access for reasons mentioned above.

The anti-dumping and countervailing investigations by the U.S. Department of Commerce (U.S. DOC) against Chinese solar PV manufacturing companies and government exacerbate the already-bad data accessibility in China. Words about government R&D investment is treated as a type of unfair subsidies by U.S. DOC made Chinese interviewees hesitate to discuss this issue. During a few interviews with Chinese researcher[16] and policymakers[17], they declined to comment on innovation investment in China because they did not want their words to be used as evidence to support the trade accusations against China, even though that was not the purpose of the interviews to begin with.

[16] Interviewee #45
[17] Interviewee #63, #73

3.6.3. Solar Innovation Investment in China

With the data difficulties being said, this study explored almost all the means possible to collect the R&D investment data since the 10th FYP. Methods for data collection include searching public databases, tracing government documents, and interviewing people who involved in funding decision-making. The results show that between 2000 and 2015, the total solar-related R&D spending from both the public and private sector amounts to $1,364 million (Table 3.4). Among which, Tier 1 Chinese solar PV manufacturing companies invested over a trillion USD in their own R&D effort.

Government programs such as the NSFC, the National Basic Research Program (the 973 Program) and the National High-tech R&D Program (the 863 Program) also have consistently supported the solar innovation efforts although the amount of investment they made accounts only a fraction of the private investment. Both government and private companies devote resources to build solar-related SKLs and SETRCs. Traceable figures in all forms of investment are accounted for in the table. Provincial and local governments are supposed to be responsible for a big portion of the solar innovation funding, because there are so many of them. However, data availability and transparency become worse at the provincial and local level. As a result, the figure for provincial and local investment in Table 3.7 does not mean to be all-inclusive. Rather, it illustrates the multiple layers of funding sources in China and the amount of funding this study is able to track at each level. Section 3.6.3.1 to 3.6.3.3 will take a look at how public and private financial resources are allocated across the technology spectrum and what they have achieved.

Table 3.7 Traceable Solar Innovation Spending in China from 2000 to 2015

Program	Investment
NSFC (Comprehensive)	$26 million
973+863 (Comprehensive)	$48 million
SKL + SETRC (Incomprehensive) (Public and private investment combined)	$190 million
Provincial Key Lab + Provincial ERTC (Incomprehensive)	$33 million

Table 3.7 Countinued

Program	Investment
Infrastructure Program	Unknown
Torch Program	Unknown
Total public innovation investment	$296 million
Chinese Tier-1 solar companies (Comprehensive)	$1,194 million
Total	$1,490 million

Note: Data collection and analysis conducted by the author as part of the Stanford China Project. Information presented at Stanford China Project workshop in Washington DC.

3.6.3.1. Solar innovation investment from the public sector

3.6.3.1.1. NSFC

Public innovation spending data in China is notoriously difficult to obtain, with only one exception – NSFC. NSFC is the only government-run innovation program in China that has a publicly accessible database disclosing information related to all the projects it supported since 2000. Using this database (NSFC, 2015), this research traced NSFC's spending on solar innovation over time across multiple technologies. The records show that NSFC's investment has concentrated on the second- and third-generation technologies, which reflects its future-oriented mission.

It is not a surprise that NSFC spends less resources on first-generation technologies, which are more mature than technologies that belong to the later generations. The first-generation technologies such as poly- and mono-crystalline solar cell and a-Si received $1.65 million research funding from NSFC between 2000 and 2015, which is roughly about half of NSFC's investment on the second-generation technologies (Table 3.8). Starting from 2012, NSFC expanded its support to HIT, a then emerging hot research area. $0.33 million has been spent on HIT since then. Appendix B details the number of projects and the amount of NSFC investment into different technologies. Figure B.1-B.3 in Appendix B describes the NSFC's support of the first-generation PV.

Among the second-generation technologies, CIGS sees an unbroken funding stream from NSFC starting from 2009, with 2014 being an exceptional year where 16 CIGS projects were awarded a total of $1.89 million. Compared to the prolific CIGS record, CdTe receive modest attention from NSFC. Although the very first NSFC grant to CdTe was awarded as early as in 2001, CdTe did not get on to NSFC's short list until a decade later. In total, there have been only four NSFC-supported CdTe research projects, comparing to 34 NSFC-supported CIGS projects. (Figure B.4 and Figure B.5 in Appendix B) The startling difference suggests that NSFC, from a strategic perspective, places its bet on CIGS rather than CdTe. This is because of two reasons. First, China wants to avoid direct competition with the world's only at-scale thin film producer – the U.S. based First Solar, which specializes in CdTe production. In order to do so, NSFC's resources have been directed to areas other than CdTe to avoid direct competition with a formidable incumbent Secondly, CdTe research in China failed to generate academic buzz due to the concerns for cadmium's environmental impact on water and tellurium's lack of natural availability. In addition to CIGS and CdTe, NSFC has also made a large amount of investment to other types of emerging thin film technologies such as nano-structure thin film, FeO_3 based technology, and etc. In total, NSFC spent $5.07 million between 2001 and 2015 on 58 thin film projects.

The third-generation solar PV technologies experience the fastest growth in research support from NSFC. They encompass new and emerging technologies such as pervoskite, organic and dye-sensitized solar PV, quantum dot, and Copper zinc tin sulfide (CZTS) 2008 marks a watershed year for emerging technologies, when the first NSFC grants were awarded to pervoskite and organic solar PV projects, and for the first time more than one dye-sensitized solar PV research project received NSFC funding in the same year. The growth in NSFC supports to these three technologies has been exceptional since then. Take organic PV for example, the number of NSFC-sponsored

R&D projects grew from 1 in 2008 to 34 in 2015, making it the number one PV technology in NSFC' portfolio (Table B.6 - B.11 in Appendix B).

NSFC's commitment to emerging PV technologies is reflected in both the number of projects it sponsors and the consistency of its sponsorship, especially in recent years. For both organic and dye-sensitized PV, at least 10 grants had been awarded to each of them every year since 2013, unlike the fluctuation observed in the first- and second-generation technologies. In total, NSFC has invested $17.9 million into researching the third-generation emerging solar PV technologies since 2000. A total of 207 grants have been issued since 2006, among which 95% took place since 2010. On average, NSFC awards $86,000 per grant for emerging technologies. (Table 3.8)

Table 3.8 NSFC's Investment in Solar PV Research from 2000 to 2015, (Million $)

Technology	Total NSFC Investment	Number of NSFC Grants Awarded	Average NSFC Investment per Grant
First Generation Total	2.98	36	0.083
C-Si	1.31	18	0.073
Amorphous Si	1.34	14	0.095
HIT	0.33	4	0.082
Second Generation Total	5.07	58	0.087
CIGS	2.79	34	0.082
CdTe	0.31	4	0.077
Other Thin Film	1.97	20	0.099
Third Generation Total	17.90	207	0.086
Organic	9.14	99	0.092
Pervoskite	3.6	37	0.094
Dye-sensitized	4.4	60	0.073
Quantum Dot	0.32	3	0.106
CZTS	0.45	8	0.056
Total	25.96	301	0.086

Note: Data collection and analysis conducted by the author as part of the Stanford China Project.

It is not a surprise that NSFC puts heavy weight on emerging technology research, given the fact that its mission is to promote fundamental research in novel technology areas. Technologies like organic, pervoskite and dye-sensitized PV are the ideal candidates because they are relative new concepts and a lot need to be learned about them. The eye-catching large number of grants given out by NSFC to these technologies allows a sneak peak into China's PV R&D innovation strategy. The fact that China is almost head-to-head with the western innovation powerhouse in solar cell efficiency of the third-generation technologies suggests that NSFC's strategy works. Section 3.4.1.2 will provide evidence of this point. For mature technologies that currently dominate the market like silicon-based solar PV and CdTe, China has a large innovation gap to overcome compared to countries like the U.S., Japan, and Germany. The causes for the innovation gap are historical and require more resources and longer time to overturn. However, for emerging technologies, China did not lag at the start line compared to the rest of the world. The strong public R&D support from NSFC suggests that China intent to move head-to-head with the world's leading innovation countries in these technology areas.

Driving mechanism 3.2: The National Nature Science Foundation of China's forward looking investment in the third-generation solar cell technologies has enabled China to stay competitive with world's leading level.

It needs to be acknowledged that, NSFC's investment is tiny when compared to the U.S. NSF's investment in solar PV, which totaled at $2.32 billion between just 2009 and 2015 (NSF, 2015). NSFC's 15-year budget is 10% of the US NSF's 5 year spending. The average size of NSFC grant is smaller than that of a typical US NSF grant, too.

3.6.3.1.2 973 and 863 Program

The 973 and the 863 Program often work in concert with the FYPs, especially during the 11th and 12th FYP periods as the planning of solar innovation got more and more nuanced. They practically implement the tasks and goals outlined in the FYPs by issuing competitive grants and soliciting project proposals. However, the exact amount of R&D investment made through these two programs is very difficult to track, especially in earlier FYP cycles. Relying on available public records and interviews with current and past funding decision-makers, this study discovers the following picture about the two flagship MOST programs.

Typical 973 grants are about $3.2 million (¥20 million) to $4.8 million (¥30 million). They usually last for 3-5 years. For the 863 Program, a small-scale project usually receives about $150,000 (¥1 million) to $500,000 (¥3 million); for a key project, the amount of financial support ranges from $3.2 million (¥20 million) to $ 8.2 million (¥50 million); for a project that is labeled as "crucial", $8.2 million (¥50 million) to $25million (¥150 million) could be allocated to support the research[18].

Through these two programs, MOST sets up innovation networks that cover major PV technologies including silicon-based solar PV, CIGS, CdTe, amorphous silicon PV, pervoskite, HIT, and multi-junction solar PV, which match perfectly with the technology priority proposed in the 12th FYP. There are also 973 and 863 projects dedicated to solve bottleneck issues in the manufacturing stage, such as the production of silver/aluminum paste, backsheet, EVA, and tooling needed in cell and panel manufacturing. Between 2012 and 2015, MOST has persistently supported solar PV research. In 2012, four solar PV projects were funded; and the numbers for 2013, 2014, and 2015 were 2, 2, and 6 (CREIA, 2014).

Based on information collected by this study, MOST's investment in solar through 973 and 863 Programs in 2013 and 2014 were 25 million RMB (about 4.1 million USD) and 18 million RMB (about 3million USD), respectively. Table 3.9 breaks down the investment by program, by technology over three FYP cycles.

Table 3.9 Traceable Solar Innovation Spending from the 973 and 863 Program in (2000-2015)

Technology	10th FYP (M$)*		11th FYP (M$)*		12th FYP (M$)^		Total (M$)
	973	863	973	863	973	863	
a-Si	2.4		2.4	2.3	4.0	3.2	14.4

[18] Interviewee #45, #52, #59

Table 3.9 Continued

Technology	10th FYP (M$)*		11th FYP (M$)*		12th FYP (M$)^		Total (M$)
CdTe		3.2		3.9		1.6	8.7
CIGS		3.5			4.8		8.3
DSSC	2.4		2.4	1.6			6.5
HIT				0.3		4.8	5.2
Black silicon					4.8		4.8
Total	4.8	6.7	4.8	8.1	13.6	9.6	47.9

Note: Data collection and analysis conducted by the author as part of the Stanford China Project.
***** Source: Interviews with funding decision-makers during the 10th and 11th FYP.
^ Source: China Renewable Energy Industry Association (CREIA) research.

3.6.3.1.3. State Key Labs (SKL) and Key Engineering and Technology Research Centers (SETRC)

There are two solar-related State Key Labs in China; both are based in large Chinese solar PV manufacturers. The PV Material and Technology SKL at Yingli and the PV Science and Technology SKL at Trina are both jointly financed by the companies and MOST. Companies are responsible for majority of the financial need of the labs. Susceptible to the same data availability problem, detailed information on how these two labs are funded is difficult to obtain. MOST publishes a list of SKLs, without detailing their R&D financing mechanism. Companies enjoy the reputation of SKLs, a status recognizing their innovation capacity, but they do not disclose the finances of the labs. As a result, the data presented in Table 3.10 are by no mean comprehensive. Instead, they represent this study's best attempt to collect information from first-hand and second-hand information sources.

There are four State Key Engineering and Technology Research Centers. The National PV Engineering and Technology Research Center at LDK, the National PV Equipment Engineering and Technology Research Center at the 48th Research Institute of China Electronics Technology Group Corporation (CETC), and the National Photo Electronic Material Engineering and Technology Research Center at CAS Fujian Institute of Material Structure Research. They represent the country's effort to tackle three key components in solar PV manufacturing: the model, tooling, and materials. However, for similar reasons, funding information for SETRCs is difficult to track. Only partial funding information about LDK's SETRC was found.

Overall, SKLs and SETRCs are integral part of China's solar innovation system, but the funding mechanism is too opaque to reveal exactly how much has been invested in these two systems by public and private sector players in China. However, judging by the hosts of SKLs and SETRCs, private companies are leading the research efforts, which means the nature of the SKL and SETRC research is inevitably practical and tailored to the need of the industry instead of being pure scientific investigation.

Table 3.10 Traceable State Key Labs and State Key Engineering and Technology Research Centers Innovation Spending

Lab/Research Center	Home Institute	Year Established	Investment
State Key Labs			
PV Material and Technology SKL	Yingli	2010	At lease $90 million investment, from both MOST and Yingli
PV Science and Technology SKL	Trina	2010	N.A.
State Engineering and Technology Research Centers			
National PV Engineering and Technology Research Center	LDK	2009	At least $100 million investment, from both National Energy Agency and LDK
National PV Equipment Engineering and Technology Research Center	48th Research Institute of CETC	2011	N.A.
National Photo Electronic Material Engineering and Technology Research Center	CAS Fujian Institute of Material Structure Research		N.A.

Note:
1. Data collection supported by China Renewable Energy Industry Association (CREIA)

2. Analysis conducted by the author as part of the Stanford China Project

3.6.3.1.4. Provincial level funding

The difficulty to track provincial level funding is two-fold. First, as discussed earlier, data availability at the provincial level is less than ideal in many cases. Compared to the central government, provincial governments are less likely to have data management system in place to track how money is spend. Second, the structure of provincial level science and technology agency and the innovation programs they administer vary from place to place. The lack of consistency across provinces is not a bad thing because it allows provinces to experiment with different policies measures, but it does make a comprehensive accounting of all the solar-PV related programs almost impossible.

With that being said, provincial level key labs and key engineering and technology research centers are two programs that can be found across the board. This study uses these two programs as an indication of provincial level government-sponsored innovation activity. Table 3.11 shows the traceable financing information about these two types of program. Very little data is publicly available. In cases where data is available, asset value instead of R&D investment is released.

Table 3.11 Traceable Provincial Key Labs and Provincial Key Engineering and Technology Research Centers Innovation Spending

Lab/Research Center	Home Institute	Year Established	Asset Value
Provincial Level Key Labs			
Liaoning Province Key Lab for Solar PV System	Dalian University of Technology	2008	$2 million in asset value
Henan Province key Lab for PV Materials	Henan Normal University, Henan University	2008	$0.8 million in asset value

Table 3.11 Continued

Lab/Research Center	Home Institute	Year Established	Asset Value
National Energy Administration PV Technology Key Lab	Yingli		N.A.
Provincial Level Engineering and Technology Research Centers			
Jiangsu Engineering and Technology Research Center for PV Vertical Integration	Trina	2008	$30 million in asset value
Jiangsu Engineering and Technology Research Center for High Efficiency Silicon PV	Altusvia Energy (Hareon Solar Affiliated)	2013	N.A.
Engineering and Technology Research Center for PV High Efficient Solar Cell	CAS Material Insitute and Xinyou Solar	2011	N.A.
Hubei Engineering and Technology Research Center for Solar PV	Wuhan Rixin Technology, Co. LTD	2005	N.A.
Hubei Engineering and Technology Research Center for Invertor and Energy Storage	Hubei Zhuiri Electric	2014	N.A.
Beijing Engineering and Technology Research Center for PV Manufacturing Equipment	Beijing Jingyi Century Electronics Co. LTD	2011	N.A.

Note:
1. Data collection supported by China Renewable Energy Industry Association (CREIA)
2. Analysis conducted by the author as part of the Stanford China Project

3.6.3.2. The Effectiveness of Public Sector Investment

3.6.3.2.1 Initial Driving Force of Solar PV R&D

It is worth noting that public finance of solar PV R&D is the earliest investment into solar innovation. It happened years before private companies became noticeable players in the field. Public investment gave the field its initial momentum. Besides, various STI programs promote public-private partnership in research collaboration, which facilitate the formation of innovation networks (Section 3.7. will discuss these innovation networks in detail). They also provide funding to new and emerging technologies, filling the void left by the private market.

Driving mechanism 3.3: Public finance investment through government science, technology and innovation programs supplement the private sector investment by supporting initial basic research into nascent and risky technologies. They also promote collaborations between academia and the industry, facilitating the diffusion of knowledge, the development of innovation network, and the commercialization of innovation products.

3.6.3.2.2. Poor Policy Consistency and Continuity

Nevertheless, it is helpful to understand China's public finance investment into solar technology in context. The magnitude of Chinese public R&D is small, compared to its own private sector and also to the United States. Between only 2009 and 2015, the Office of Science under the U.S. Department of Energy (U.S. DOE) alone spent at least $321 million on solar related research (Steyer-Taylor Center for Energy Policy and Finance, 2016). In addition, the U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE), the ARPA-E program, and the U.S. National Science Foundation (NSF) all contributed to solar innovation in the U.S. in larger amount than the Office of Science. With the U.S. context, it is fair to say that the traceable solar innovation spending in China is small. Even if inflation and cost of living adjustments are taken into account, China's public finance investment in solar innovation is still far from comparable to the situation in the U.S. Granted, research dollar stretches longer in China given the relatively lower cost to hire researchers, lower cost of living, and lower cost to do almost everything else, it is still striking to see how small the public R&D investment is in China.

People close to MOST policymaking[19] and a Chinese solar entrepreneur[20] all admitted that Chinese government and companies currently only spend a fraction of what the U.S. government and private companies spend on solar innovation. Even though the actual amount of public solar PV innovation investment is rising every year, it is going to take a long time before China catches up to leading innovative countries in the West. Given that, the Chinese's plan is to do more with less. It meant to use innovation spending through the STI programs to create a "technology to market" cycle, which in theory is an effective way to invest in innovation. In an interview with MOST's chief solar PV scientist, he revealed the thinking behind MOST's attempt to support the full RDD&D cycle of key solar PV technologies over multiple FYPs. [21]

1. Ideally, MOST would support the initial fundamental physics research through the 973 Program (the basic science oriented program). A successful project would produce a small area prototype solar cell with decent efficiency.
2. Then in the second FYP, MOST would use the 863 Program (the more practical-minded program) to support the research of transferring the small area lab-made solar cell to a commercializable product. The ideal result of this stage would be a pilot cell production line.
3. Lastly, in the third FYP cycle, MOST would provide seed fund via the infrastructure program to incentivize the commercialization of the product. At this stage, equipment manufacturers and cell producers would typically collaborate to realize the mass production.

In concept, this is a sound approach. However, in practice, MOST's support of technology innovation often lacks the continuity and the persistency that it inspires to provide. Table 3.12 reviews a list of MOST supported programs in the past 3 FYP cycles; the only technologies loosely resemble the ideal approach are DSSC, a-Si, and CdTe.

[19] Interviewee #64, #93
[20] Interviewee #65
[21] Interviewee #73

Table 3.12 Number of MOST 973 and 863 Programs in the Past 3 FYP Cycles by Technology*

Technology	10th FYP		11th FYP		12th FYP		Total
	973	863	973	863	973	863	
a-Si	1		1	1	1	2	6
DSSC	1		1	1			3
CdTe		1		3		1	5
CIGS		1			1		2
HIT				2		2	4
Black Silicon				1			1
PERC						1	1
Total	2	2	2	8	2	6	22

* Notes:

1. Information on the Infrastructure program is not available.
2. Table B.1 in Appendix B shows the actual amount of funding broken down by technology and MOST program over the same three FYP cycles.
3. Data collection and analysis conducted by the author as part of the Stanford China Project

In general, even though MOST's funding allocation records show some consistency and continuity in certain technology space, the effectiveness of its support is debatable. The 973 Program initially supported DSSC and a-Si during the 10th FYP. The support continued to the 11th FYP with both technologies receiving funding from the 863 Program in addition to the phrase II support from the 973 Program. Research funding was made available again to a-Si in the 12th FYP while it ended for DSSC. Despite the consistent support, DSSC and a-Si technology have not reached the maturity for commercialization yet. In fact, few people sees them as viable candidates for mass market adoption. CdTe faces a different issue. American company First Solar has proved its market feasibility, but in China, only Advanced Solar Power (Long Yan) is able to achieve an at-scale production (350 MW) and it was not even supported by the 863

Program until 2014. Yet the two CdTe projects supported by the 863 Program in the earlier years did not demonstrate any significant real world commercialization achievement. Arguably, HIT and PERC may be the only successful examples of MOST's investment. For both technologies, prototypes invented in China are currently produced by leading Chinese companies at a large scale.

3.6.3.2.3. Incompetent Technology Forecasting and Inaccurate Market Assessment

MOST's lack of policy continuity and consistency is a result of its weak ability to conduct technology forecast and follow market trend. As one well-regarded Chinese solar scientist said " Government is very bad at detecting what types of innovation holds scientific and market potentials."[22] Historically, MOST and its predecessors followed the command and control approach where they do everything, from setting goals, picking promising technologies, raising and allocating resources, and singled-handedly supporting the entire cycle of technology development.

The outcome of such approach is far from ideal. As seen in Table 3.12, MOST continuously invested in a-Si nor DSSC, aiming for their commercialization, but neither technology is considered as ripe for today's market, not for the near future either. If MOST's ultimate goal is to allow Chinese firms to reap the economic returns generated from mass-production of these technologies, then it fails at its goal badly.

MOST's unsuccessful attempted at building the "technology-to-market" pipeline can also be seen through CdTe and CIGS. For CdTe, it has been constantly supported by the 863 Program instead of the 973 Program, which means that MOST views the need for CdTe research falls more on the applied science side than on the basic-science side. However, evidence shows that CdTe cell efficiency progressed very slowly in China and the efficiency gap between the best Chinese CdTe cell and the world record CdTe cell is becoming bigger and bigger (see Section 3.4.1.3), suggesting that CdTe research in China

[22] Interviewee #45

is still at its early stage where many fundamental scientific issues need to be addressed. This indicates MOST's inaccurate assessment of the technology development stage of CdTe. Furthermore, the five 863 projects did not bring China any closer to successfully commercialize CdTe solar cells. The only CdTe manufacturer of consequences in China is the Hangzhou based Advanced Solar Power (ASP), and it achieved commercial production without any support from MOST programs.

CIGS is another contradictory example to MOST's policy design in the sense that it started with the 863 Program (applied research) in the 10th FYP but later was switched to the 973 Program in the 11th FYP, indicating that MOST first thought the commercialization of CIGS was within sight but only to realize years later that there were more fundamental science work to be done in this area. Fortunately, CIGS research in China did not completely rely on the STI programs under MOST. Rather, university- and research institute-funded projects complemented MOST' effort, and they produced significant improvement to the cell efficiency of CIGS.

Both examples of CdTe and CIGS illustrate MOST's incapability in forecasting technology development path and setting technology development agenda. MOST does not demonstrate to have the best judgment about which technologies are commercialization-ready and which ones are still at early stage. This is because of three reasons. First, compared to private market players, government agencies like MOST are less in tune with the market demand for technologies. Second, even with accurate technology forecast and the ideal policy design in mind, when it comes to the project selection process, MOST's decisions are often affected by the availability and quality of proposals. Interviews with policymakers at MOST [23] and scientists[24] who were involved in the 973 and 863 project selection process revealed that sometimes, projects were not awarded to certain technology not because of a lack of intention to do so but due to the

[23] Interviewee #73
[24] Interviewee #45, #59, #73

lack of high quality project proposal. Finally, MOST relies on academic consultants for advices about technological trend, which makes it susceptible to academic bias, or even academic lobbying. Anecdotes about some government science advisors exaggerating the potential of the technologies they work on over others have certainly been passed around in the academic circle, although no investigation has been done to look into the allegations.

Evidence presented above show that government is bad at predicting technology trajectory and they do not have a good sense about the market demand of technologies. Therefore, they are not able to allocate resources in an effective and productive way. It puts the government in an awkward situation. On the one hand, it wants to push for a practical innovation agenda that produce industry-oriented and market-friendly outputs. On the other hand, without engaging players from the private sector, the bureaucrats inside the government have little information about what the industry and market need.

Blocking mechanism 3.3: A lack of consistency and continuity, the less-than-perfect technology forecast, and the inaccurate market feasibility assessment rendered MOST's utilization of the science, technology and innovation programs inefficiency and ineffective.

In summary, from the policymaking's perspective, MOST has the good intention to bridge the gap between lab research and industrial production. It sent policy signals to encourage academic-industry collaboration; it also intended to use its flagship innovation programs strategically to facilitate technology transfer from the labs to production lines. However, the effectiveness of its programs suffers from a lack of consistency and continuity, their less than perfect technology forecast, and their inaccurate market feasibility assessment.

3.6.3.3. Solar Innovation Investment from the Private Sector

Chinese solar PV manufacturing companies' R&D spending experiences two phrases. Before 2011, companies' investments into R&D were minimal. Most firms spent less than 1% of their total revenue on R&D. Yingli, Trina, Suntech and ReneSola showed stronger R&D investment record relative to their peers during this period, investing about 1.5% to 2% of their total revenue in research. Since 2011, there has been a clear trend of companies up their game in R&D spending, a good number of Chinese firms doubled or even tripled their investment in R&D.

There are two reasons as to why R&D investment among Chinese companies increased significantly in recent years. On the market side, one silver lining of the anti-dumping and countervailing duties levied by the U.S. and the quota and price floor imposed by E.U. is that they made Chinese firms look for sources of competitiveness at places beyond just low costs. The higher R&D investment is a sign that Chinese firms started to take product innovation seriously, hoping it can yield long-term benefit for the companies.

In addition to companies' internal drive to invest more in R&D, government policy also played an unequivocal role in driving up R&D investment. In 2013, in the mist of the PV manufacturing sector reform in response to the trade cases, MOIIT issued the PV Manufacturing Industry Standards, in which it set a lit of R&D-relate criteria to PV manufacturing firms. The Standards required firms to spend at least 3% of its revenue and no less than ¥10 million ($1.6 million) every year on R&D. All companies are required to adhere to the criteria laid out by the Standards in order to continue stay in business in China. The importance of this government policy is that it set an industry-wise floor for R&D investment. The result of implementing the Standards is that industry-wise R&D investment systematically went up while weaker players in the industry were forced to exit the market.

Table 3.13 summarizes the innovation spending of current and previous Tier 1 Chinese solar PV manufacturers between 2006 and 2014, ranked by their 2014 amount.

Cumulatively, these 9 companies spent $1.19 billion in R&D over 9 years, eclipsing the traceable amount of investment from the public sector by more than three-fold.

The relative weight between public and private investment into R&D is consistent with the official rhetoric from Chinese government, which calls for the private sector actors to play the leading role in innovation while the government plays only a supporting role. Despite the relative big R&D spending, Chinese companies are still behind their American competitors by a long shot in the actual R&D investment. Table 3.14 shows the R&D spending from American tier 1 companies. They on average spend 2.2 to 8.6 times more in their in-house research. First Solar stands out as the largest corporate innovation player, investing well over $100 million per year since 2011, 6 times greater than average Chinese firms.

Table 3.13 Chinese Solar PV Manufacturing Companies Innovation Spending Ranked by 2014 Value (Million$)

Company	2014	2013	2012	2011	2010	2009	2008	2007	2006
Yingli	92.62	47.21	29.82	44.36	20.52	27.00	8.37	1.33	N.A.
ReneSola	52.58	46.45	44.10	47.06	36.26	14.51	9.71	1.39	N.A.
JA Solar	22.66	14.38	13.67	10.74	9.49	6.60	4.14	0.55	0.08
Trina	22.26	19.93	26.51	44.12	18.63	5.44	3.04	2.81	0.19
Jinko	17.31	10.68	9.10	3.61	4.26	N.A.	N.A.	N.A.	N.A.
Hanwha	13.80	15.06	14.45	10.67	7.94	4.69	2.88	3.76	0.49
Canadian Solar	12.06	11.69	13.00	19.84	6.84	3.18	1.83	0.39	0.04
LDK	0.00	10.98	17.78	46.51	10.80	8.30	7.57	2.94	N.A.
Suntech	N.A.	N.A	8.90	36.87	40.26	29.02	15.31	15.06	8.37
Total	233.29	176.38	177.33	263.77	155.01	98.74	52.85	28.22	9.17
Average	33.33	22.05	19.70	29.31	17.22	12.34	6.61	3.53	1.83

Notes:

1. Data source: Bloomberg Terminal Tier 1 company profitability data.
2. 2014 data include only the first two quarters.
3. Data are not available for Yingli and ReneSola, and LDK in 2006, and Jinko from 2006 to 2009 because companies were not publicly listed in these years or because they did not report R&D spending information to the U.S. Security Exchange Commission.
4. Data are not available for LDK in 2014 and Suntech in 2013 and 2014 because they were delisted from public stock market.

Table 3.14 U.S. Based Solar PV Manufacturing Companies Innovation Spending (Million$) Ranked by 2014 Value

Company	2014	2013	2012	2011	2010	2009	2008	2007	2006
First Solar	71.4	134.3	132.5	140.5	94.8	78.2	33.5	15.1	1.7
SunEdison	31.6	71.1	71.8	87.5	55.6	51.0	40.8	39.3	35.8
SunPower	33.3	58.1	63.5	57.8	49.1	31.6	21.5	13.6	9.7
SolarCity Corp	17.2	0.4	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
SolarWorld	N.A.	36.1	63.8	N.A.	3.0	17.7	N.A.	N.A.	15.8
Total	296.3	299.6	331.5	285.8	202.5	178.5	95.8	68.0	63.0
Average	74.1	74.9	82.9	95.3	50.6	44.6	31.9	22.7	15.7
American/Chinese Ratio	2.2	2.7	4.2	3.3	2.9	3.6	4.8	6.4	8.6

Notes:

1. Data source: Bloomberg Terminal Tier 1 company profitability data.
2. 2014 data include only the first two quarters.
3. Data are not available for SolarWorld in 2007, 2008, 2011 and 2014 because it did not report R&D spending information to the U.S. Securities and Exchange Commission.

To summarize, evidence of companies' financial commitment to innovation suggests that Chinese firms are increasingly attentive to the idea that innovation is important to a firm's long-term competitiveness. They are the predominant investor in the first-generation solar cell R&D, eclipsing public finance investment by a magnitude. Collectively, they are the largest sponsor group of solar innovation in China, although their level of R&D spending is only a fraction of what is spent by their American competitors, suggesting that American companies still maintain a competitive edge on innovation over Chinese firms.

3.7. Innovation Networks and Their Impact on Solar PV Innovation

3.7.1. Macro Level: Innovation Ecosystem

At the macro-level, there is a solar innovation ecosystem that facilitated by the MOST-run STI programs. They work as intermediaries to funnel national-level public innovation investment to the actual innovation players on the ground. Individually, each program occupies a niche in the technology development cycle with a certain level of overlap with its adjacent programs by design. Collectively, they cover the entire RDD&D spectrum, as shown in Figure 3.11. Simply put, MOST divides the programs into two groups: programs related to fundamental scientific research, such as the 973 Program and the coordination with NSFC, are managed by the Office of Basic Research. Their principle function is to spur ***knowledge development and diffusion.*** Programs such as the 863 Program, the Infrastructure Program, and the Torch Program are administered by the Office of High and New Technologies. Besides ***knowledge development and diffusion,*** they also try to ***create*** a commercial ***market*** for technologies and ***develop positive externalities*** that transcend the innovation subsystem.

Depending on where they are on the RDD&D cycle, different STI programs incentivize, sometimes even requires, certain types of collaborations to be formed between research entities and private sector players in order to qualify for government-sponsored solar innovation projects. For example, the basic research oriented 973 program is instrumental in establishing collaboration between university-based research group and other research institutes. In contrast, the more applied-research-oriented 863 Program prioritizes projects that are jointly conducted by research organizations (universities and research institutes included) and industry players. State Key Labs and State Engineering and Technology Research Centers are often based in solar PV manufacturers to support the company-driven, research organization-supported innovation model. The Infrastructure Program built commercialization networks that link PV products developed in research institutes with companies that have production capacity.

The importance of the innovation ecosystem is that it builds a virtual infrastructure through which innovation players interact with one another and develop technology-specific innovation networks, which will be explored in details in next section.

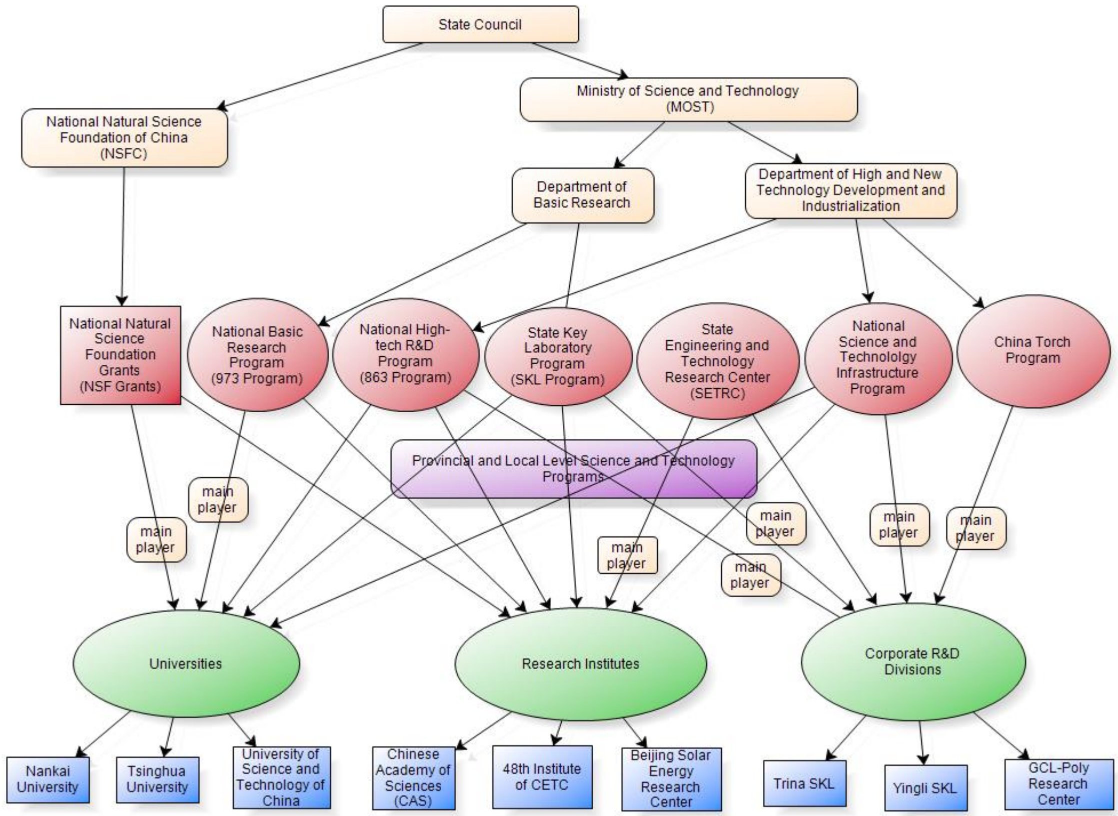

Figure 3.11 Innovation Ecosystem in China

Note:
1. Analysis conducted by the author as part of the Stanford China Project.
2. Information presented at Stanford China Project workshop in Washington DC.

3.7.2. Micro Level: Technology specific innovation networks

The PV innovation ecosystem provides the right condition for technology-specific innovation networks to form. Drawing from insight collected over dozens of interviews with R&D experts from respective technology areas, over a dozen laboratory visits, as well literature review and data mining, this study discovers that innovation networks allow China to draw knowledge from a wide range of sources and use them to fill the historical knowledge gaps and therefore, improve its own innovation strength and achieve innovation progress. Interestingly, the innovation networks take on different forms; some are built on collaborations between institutions while others rely on key individual figures. Nevertheless, one common feature they share is that the networks are global. The collaboration with overseas research institutes and the recruitment of academics with overseas training experience have meaningful contribution to the narrowing of the innovation gap between China and the developed world.

This section zooms into specific technologies and maps out the innovation networks for the same five types of solar cell, the efficiencies of which were examined in Section 3.4.1 of this chapter. It means to test Hypothesis 1 through examining the formation of individual technology specific networks under the context of the broader innovation ecosystem and analyzing the link between them and the outcome in solar cell efficiency improvement.

Hypothesis 1. Innovation networks facilitate knowledge production and diffusion, which lead to innovation progress.

3.7.2.1. HIT Innovation Network: Big Institution Collaboration

HIT research does not have a long history in China. It was not until the 11th FYP (2005-2010) when China launched two 863 HIT research projects that the country officially started HIT research. A group at the CAS Institute of Electrical Engineering (IEE), led by Dr. Wenjing Wang, was the first research institution to work on HIT in China. During the 11^{th} FYP period, it received 80,900 RMB ($13,500) from the 863 Program to work on a joint research program with Shanghai Jiaotong University and Shanghai Chaori Solar, a China-based PV manufacturing company.

As earlier mentioned, MOST's emphasis on engaging private sector players in innovation became more and more prominent during the 12^{th} FYP period. Two more HIT projects were sponsored by the 863 Program and both are joint R&D venture by company and research institute. Building on the foundation it established during its previous 863 project, the group at CAS IEE teamed up with Shanghai Chaori Solar again to further improve the efficiency of HIT cells and explore its commercialization. As of 2013, the collaboration produced an HIT solar cell at 20.25% efficiency. Another 863 project was conducted by Trina and CAS Shanghai Institute of Microsystem and Information Technology (SIMIT), led by a Dr. Zhengxin Liu, a Thousand-Talent program recuritee. Dr. Liu horned his HIT research skill in Japan, the country that is the most advanced at HIT research. He received his doctoral degree from a Japanese University and worked at leading Japanese research institutes including the System Engineers Co., Ltd. and the National Institute of Advanced Industrial Science and Technology before he was recruited by China's Thousand-Talent Program to come back to China in 2009. Since joining CAS Institute of Microsystem and Information Technology, Dr. Liu quickly developed his research group to be the leading player in HIT research in China. His group's collaboration with Trina yielded the highest-efficient HIT cell in China as of 2013, reaching 22%. The ongoing collaboration between the two continues to push the efficiency boundary.

In addition to the 863 projects, Chinese companies are collaborating with overseas research institutes. Yingli, together with the Energy research Centre of the Netherlands (ECN) has produced HIT solar cells of 20-21% lab efficiency. Suntech established a collaborative relationship with Fraunhofer ISE (the efficiency is unknown). (Figure 3.12)

Evidence shows that the improvement of HIT cell efficiencies in China as seen in Figure 3.3 in earlier sections is largely a result of collaboration between Chinese companies and domestic and international R&D partners. The research networks they form enabled the efficiency progress.

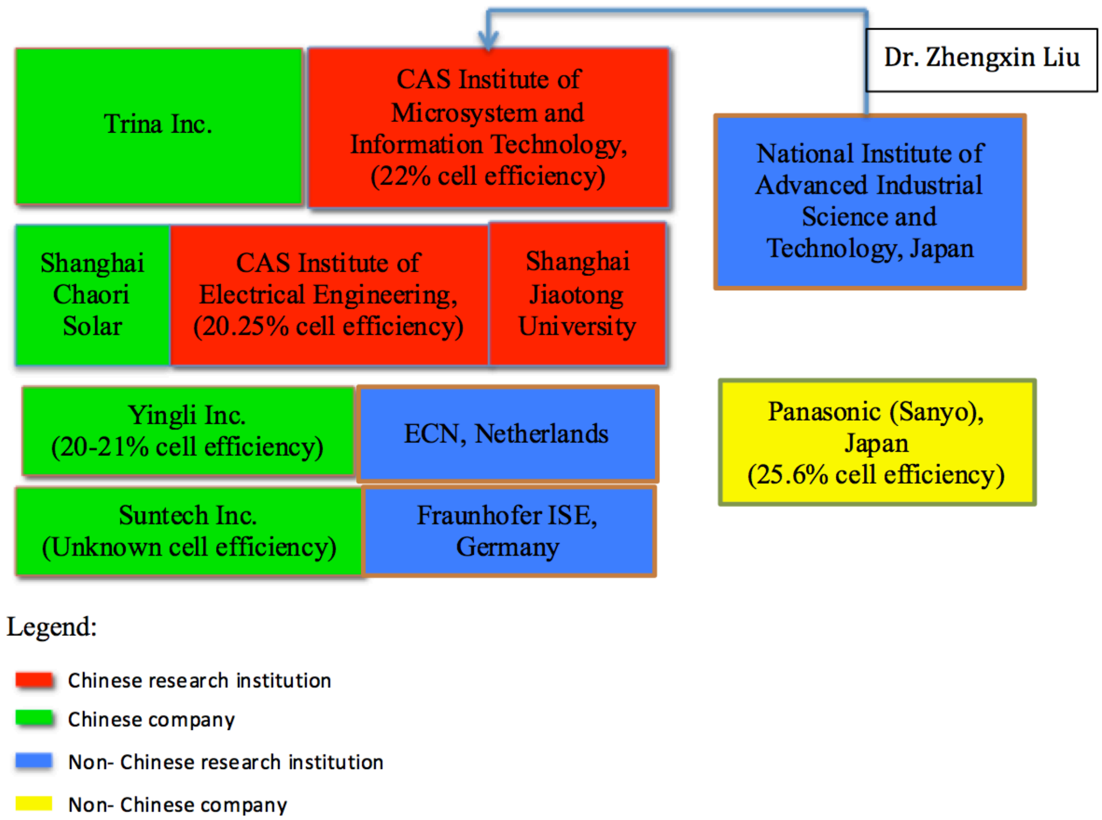

Figure 3.12. HIT Innovation Network: Big Institution Collaboration

Note:
1. Data collection, and significant data analysis, conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
2. Information presented at Stanford China Project workshop in Washington, DC.

3.7.2.2. CIGS Innovation Network: Domestic Collaboration and Foreign Acquisition

The innovation network for Copper Indium Gallium Selenide (CIGS) features low profile domestic academic-industry collaboration and high profile overseas acquisition.

There are many organizations working on CIGS solar cells in China currently. CIGS started to receive the funding since the 8th FYP, but it was not until the 863 project during the 10th FYP that the CIGS research started to produce substantial outcome. Nankai University was among the first Chinese institutes to work on the technology.

With R&D investment from MOST, Nankai mastered the techniques to self-design the equipment to produce CIGS solar cells and collaborated with Taiyang Company in Tianjin to build a pilot production line with the funding from the 863 project in the 10^{th} FYP period. However, the production was not eventually shut down because it was not economically sustainable.

Overseas returnee plays a big role in recent years. The group at CAS Shenzhen Institutes of Advanced Technology led by Professor Xudong Xiao emerged since 2010 and established itself as the new leader in CIGS research in China. It produced a 19.07% CIGS cell in 2013, only 1% lower than the world record of the same year (Figure 3.4). It has significantly narrowed the gap between China and the world's leading research. Dr. Xudong Xiao received his Ph.D from University of California at Berkeley in the U.S. and did his Postdoc training at Lawrence Berkeley National Laboratory in the U.S. He was recruited by the Thousand-Talent program and returned to China and took post first at Hong Kong University of Science and Technology in 2004 and then at the Solar Research Institute in Shenzhen Institutes of Advanced Technology in 2008.

Other leading institutions of CIGS solar cells include Professor Yaoming Wang's group in Shanghai Institute of Ceramics (CAS), Professor Daming Zhuang's group in Tsinghua University, Beijing University, Shanghai Institute of Technical Physics (CAS), and Shenzhen institute of advanced technology (CAS). Many of these institutions collaborate closely with companies to develop pilot production lines. Tsinghua University worked with two private solar companies, Lanxing Terra Company at Weihai, Shangdong Province and Dikai in Guangxi Province. Peking University built a pilot production line with BESC in Henan Province as part of an 863 project; CAS Shenzhen Institute of Advanced Technology built its own 2MW pilot line using self-developed manufacturing techniques and equipment design. Nevertheless, none of these production lines scaled up.

The only at-scale CIGS manufacturer in China is Hanergy. Hanergy represents a different and unique innovation model. For a while, Hanergy was a celebrated case and got a lot of media attention. Instead of building its indigenous innovation capacity, the company has garnered R&D strength through a list of high profile global merge and acquisition. It acquired five overseas innovative thin film solar PV companies and became the owner of their R&D profiles (Exhibit 6 in Appendix B details the companies Hangery purchased and their technology profiles). Its global R&D center in Beijing is the central management entity that oversees its global research network. No actual research is conducted in its Beijing center. Hanergy's goal was not to build its indigenous innovation capacity, but to acquire overseas promising thin film technologies that struggle with commercialization and marry them with China's strong manufacturing capacity. By acquiring these companies and the intellectual properties and R&D capacity behind them, Hanergy internalized advanced CIGS knowledge into its own operation in China, narrowing the knowledge gap between China and world's leading CIGS innovators[25]. Its mergers and acquisitions strategy expanded the scope of the CIGS innovation network in China and brought progress to innovation outcomes. Figure 3.13 illustrates the major R&D players in CIGS field. Commercialization activities are not included.

[25] Hanergy is reported to show financial and operational problems in recent months. http://www.ft.com/ft-investigations

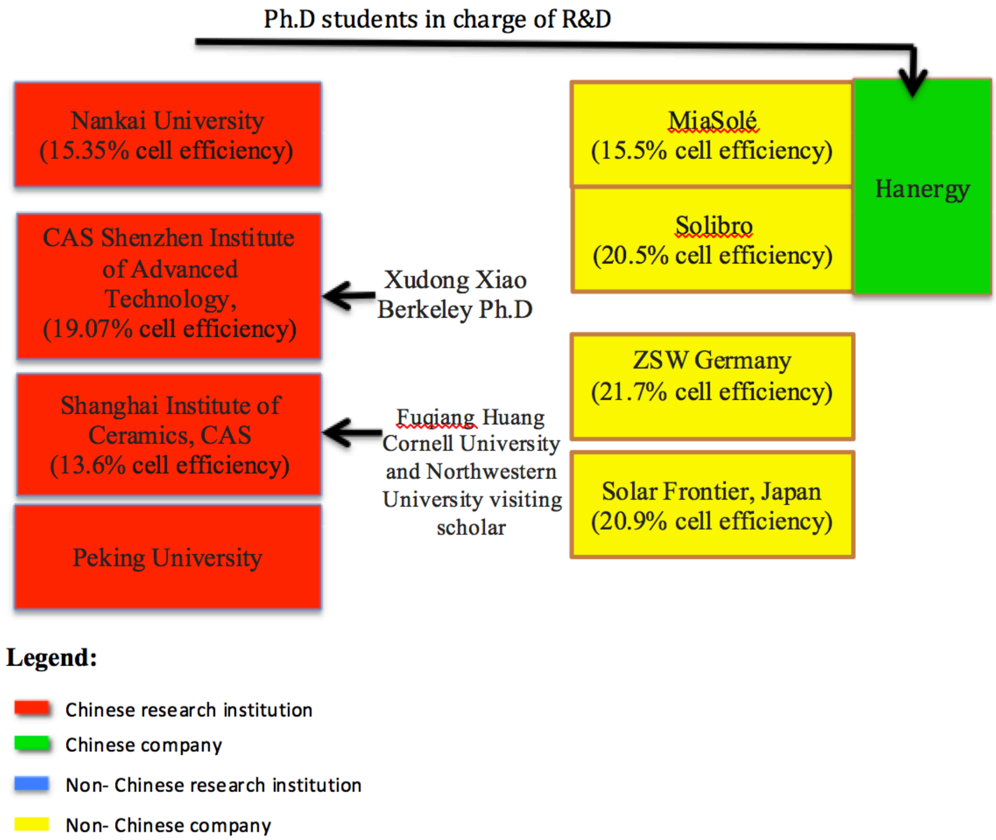

Figure 3.13 CIGS Innovation Network: Research and Foreign Acquisitions

Note:
1. Data collection, and significant data analysis, conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
2. Information presented at Stanford China Project workshop in Washington, DC.

3.7.2.3. CdTe Innovation Network: Returnees from Overseas

CdTe solar cell in China started as early as 1980s, but government funding in this area has not been sufficient. NSFC started to fund CdTe research after 1990s but the amount of the funding was small, varying from tens to hundreds of thousand RMB. Two small scale CdTe-related 973 and 863 projects were launched during the 10th FYP (1995-2000). Paralleled to the mundane government support was an inactive research field. There were only a few research group actively worked on CdTe research, the most noticeable among which was Sichuan University. It achieved an efficiency of 13.38% in 2001 with the support from the 863 Program. Its 300 kW-level pilot production line can produce 40cm x 30cm solar modules at an efficiency of 8.25%. But that was about all the achievement in this technology space in the first decade of the 21st century. As seen in Figure 3.7, CdTe research in China experienced a long period of stagnation. Between 2000 and 2012, little cell efficiency improvement was made.

Fortunately, the CdTe research landscape started to turn around in the 2010s. There has been an uptake in research interest and an increase in innovation players. One common characteristics of the new-coming players is that they all have strong overseas education and research background. Dr. Xiangxin Liu of Institute of Electrical Engineering (CAS) received his Ph.D degree from University of Toledo – the birthplace of CdTe – and went back to China via the Hundred-talents Program of Chinese Academy of Sciences. His group succeeded in producing a 0.02cm2 CdTe cell at 14.4% efficient in 2014. Shanghai Center for Photovoltaic, together with Professor Deliang Wang from China University of Science and Technology, managed to produce a CdTe cell of nearly 14% efficient on a 0.07cm2 glass substrate in 2012 and 14.6% efficient of 0.25 cm^2 using chemical bath deposition method. Dr. Wang, received his Ph.D degree from Goettingen University in Germany and worked in Japan and the U.S. In the commercial space, Dr. Xuanzhi Wu, the founder of ASP, had decades of research experience at NREL before return to China as an entrepreneur. Dr. Xuanzhi Wu, a Chinese native and former senior researcher at NREL who set the world record CdTe efficiency in 2002, founded Advanced Solar Power (ASP) in Hangzhou, China in 2008. ASP's module efficiency stands at about 12% in 2014, compared to the 14% commercial efficiency of U.S.-based First Solar. The company is producing 30MW capacities annually with self-designed equipment.

The story of CdTe research in China once again provides evidence that an innovation network (a global innovation network in this case), drive the progress in solar cell research in China. The historical knowledge gap is difficult to be overcome with endogenous forces. However, with an innovation network that connects innovation players from all around the globe, the gap can be narrowed. Even though there is still quite a distance between the record CdTe efficiency in China and the world level, the injection of foreign-trained researchers and the knowledge they bring and the research network they form are changing the research landscape in China.

Figure 3.14. CdTe Innovation Network: Returnees from Overseas

Note:
1. Data collection, and significant data analysis, conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
2. Information presented at Stanford China Project workshop in Washington, DC.

3.7.2.4. Organic PV (OPV) Innovation Network: Chinese Scholars with Overseas Experience

Research on OPV in China shows how a global network can facilitate technology leapfrog in China (Driving mechanism 3.1). There are two competing OPV research groups, both lead by researchers who are China-educated but established international networks.

Professor Yongfang Li from CAS Institute of Chemistry is the pioneer of OPV research in China. His research group produced an OPV cell of 2% efficiency in 2002. After retired from CAS Institute of Chemistry, he worked with a research group from Suzhou University and had improved OPV efficiency to about 8%. Although educated in China in the 1970s, he kept close communication with world's leading OPV research groups. From 1997 to 1998, he was a visiting scholar at Dr. Alan Heeger's group at University of Santa Barbara (UCSB), which set multiple world efficiency records. Again in 2000, he visited Dr. Yang's group at UCLA for a year, another world's leading research group. Keeping up with world's leading institutes has allowed Li to stay on top of the latest research methodology and produced prolific research outcome.

Another key OPV research group in China is led by Professor Yong Cao from South China University of Technology. Cao has a long history of participating in the global research community. He received his Ph.D degree from Tokyo University. He was a visiting scholar in Heeger's group at UCSB from 1988 to 1990 and worked as a senior researcher at UNIAX, a company co-founded by Alan Heeger, from 1990 to 1998. Cao's research group is head to head with Li's group in OPV research. The efficiency records show in Figure 3.6 are mostly results of these two groups leveraging their global innovation networks.

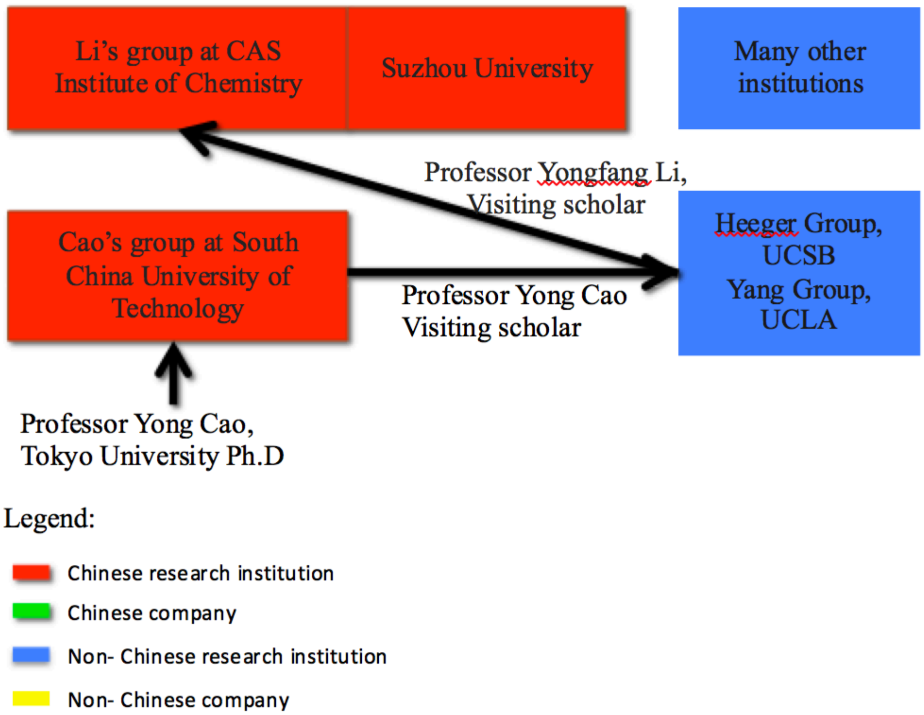

Figure 3.15. Organic PV Innovation Network: Chinese Scholars with Overseas Experience

Note:

1. Data collection, and significant data analysis, conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
2. Information presented at Stanford China Project workshop in Washington, DC.

3.7.2.5. Perovskite Innovation Network: A Combination of Overseas Returnees and Chinese Innovation

Hong Kong University of Science and Technology produced the first Chinese-made perovskite solar cell of 4.87% efficient in 2013. Back then, there were only a few institutions in China working on Perovskite, such as Dr. Liduo Wang's group at Tsinghua University, Dr. Hongwei Han's group at Huazhong University of Science and Technology, Dr. Qingbo Meng's group at CAS Institute of Physics. However, since 2013, there was a sharp increase in perovskite research in China. Because Perovskite and Dye Sensitized Solar Cell (DSSC) share similar scientific framework, many researchers who used to work on DSSC transitioned to perovskite research due to the promising prospect of the latter. The influx of innovation players created academic competition among the first generation research groups and the newcomers such as Dr. Rui Zhu's group at Peking University, Dr. Wang Peng's group at CAS Changchun Institute of Applied Chemistry, etc. Some of the leading perovskite work in China was carried out via collaboration with world's top research groups. Dr. Hongwei Han maintained a long-term collaboration with the Gratzel group at EPFL in Switzerland, where he received his Ph.D degree, on DSSC and now both have shifted their interests to perovskite. Moreover, some group leaders have once did research in the world's leading research groups. Dr. Rui Zhu received his Ph.D degree at Yang's group in UCLA on organic solar cells. Dr. Qingbo Meng was a STA fellow in Japan from 1999 to 2002. Figure 3.16 illustrates the research networks.

Although most of the early perovskite research was not funded by the government, with the surge in research interest, both the 863 and 973 Program categorize the technology as major areas for support in 2014. Today, perovskite is a heated research area in China. For example, more than 500 researches attended the first Conference on Perovskite Solar Cells & New Generation Solar Cells in Beijing in May, 2014.

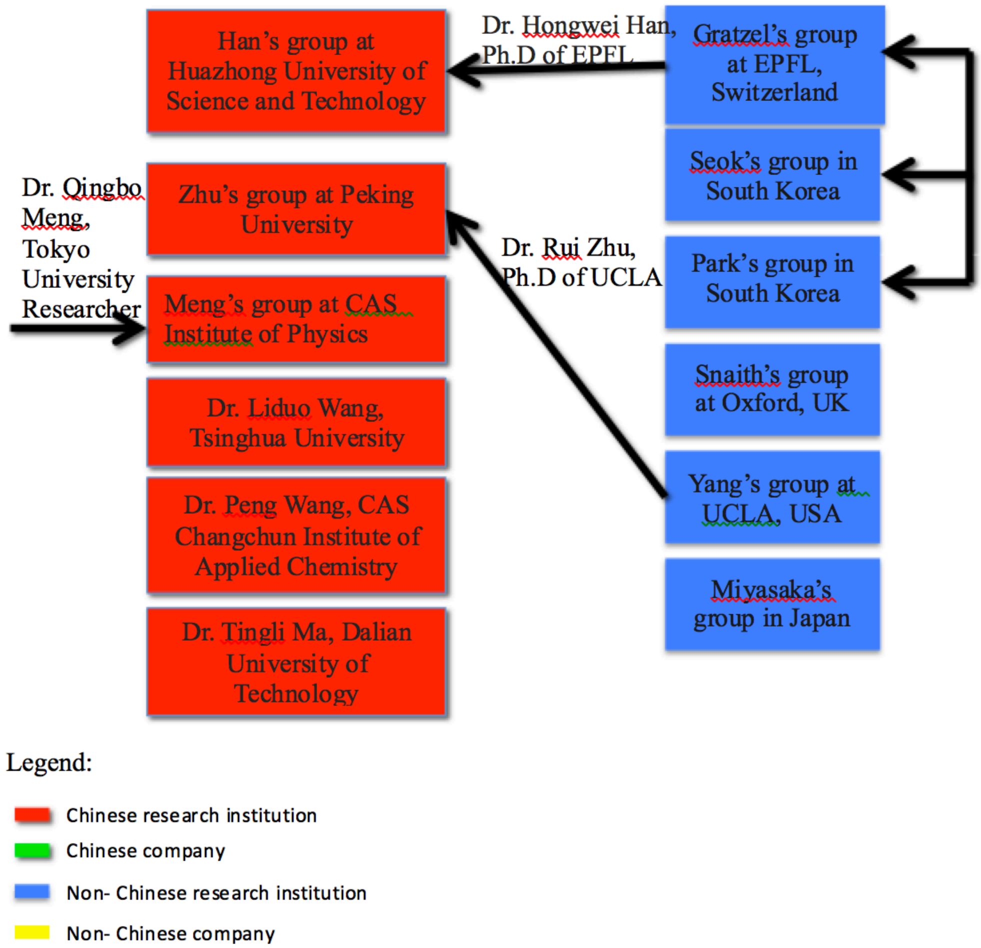

Figure 3.16. Perovskite Innovation Network: A Combination of Overseas Returnees and Chinese Innovation

Note:
1. Data collection, and significant data analysis, conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.
2. Information presented at Stanford China Project workshop in Washington, DC.

These 5 cases of technology-specific innovation network highlight different ways that players interaction with each other under the formal institution. One thing they have in common is that they all leverage the globalization trend to access overseas knowledge, education, and research capacity. Research networks are formed not only between Chinese academic and industry players (such as in the case of HIT) but also between Chinese industry players and overseas research institutes (such as the Yingli-ENC case in HIT and the Hanergy case in CIGS) as well as between Chinese academic players and overseas research groups through formal research collaboration (like the Han-Graztel collaboration in perovskite) and personnel exchange in forms of doctoral education, visiting scholar program, etc. These diverse modes of innovation network construction and knowledge exchange are shown to be the driving force of solar cell efficiency improvement in China. They serve as evidence that innovation networks, especially global innovation networks lead to solar PV innovation progress in China. As a result, this study fails to reject **Hypothesis 1.** Rather, it found that the Driving mechanism 3.4 to be true.

Driving mechanism 3.4: The solar PV innovation subsystem in China built global innovation networks to take advantage of overseas research and educational resources and achieved technological advancement in multiple areas.

3.8. Conclusions

3.8.1. Summary of Findings

This chapter studies the Chinese solar innovation TIS subsystem. It is found that formal and informal institutions significantly shape the structure of the subsystem, the networks and the interactions among actors. The subsystem has produced some progress in terms of advancing solar cell research and manufacturing capacity, and generated higher efficiency solar cells and an increasing number of papers and patents. However, although China is catching up quickly, it is still not at the frontier of the field. The innovation culture in China is pragmatic and practical, which results in more incremental improvement than breakthroughs.

More specifically, the subsystem takes advantage of the visions and strategies developed in Five year Plans for PV technology advanced to build legitimacy and mobilize resources. The plans get more and more nuanced, cohesive, executable and measurable over time. A suite of STI programs administered by the Chinese Ministry of Science and Technology carried out the implementation of the visions. The programs cover the entire RDD&D spectrum, aiming to provide comprehensive support to the entire "lab-to-market" span. FYPs and MOST's STI programs are important institutions that undoubtedly influence the direction of search of the actors in the solar PV innovation TIS subsystem. Human and financial resources have been channeled to solar PV research because of the clear policy signals the plans and programs sent. The initial financial support they provided also helped. Networks between private sector industry players and academic researchers grew stronger under the guidance promoted by MOST. Both industry and academic players' global innovation networks also expanded due to market dynamic and policy incentives. The tighter connection between public and private players and their broader global networks become one of the driving forces in the system.

Another important driving force is the growing amount of input to the system, in both capital and human resource form. In general, Chinese PV companies play a leading role in financially investing in solar PV innovation. This is consistent with China's industry-oriented, practical innovation approach. It also reflects the maturation of the industry, which has gradually evolved from competing for low price to replying on innovation to stay competitive in the market. By getting companies more involved, solar innovation in solar PV TIS subsystem leverages both the corporates' financial resources and their knowledge about the market's demand for technologies. The latter also serves as a remedy to the government's inability to set the right technology R&D agenda due to its lack of ability to accurately capture the technology trend in the markets.

The subsystem is found to be able to produce substantial outcome in certain areas. An analysis of three generations of solar PV technology showed that company-led, universities and research institutes-supported R&D efforts produced the most significant outcome for the first-generation solar PV technologies. For the second-generation technologies, universities, research institutes and companies work independently, without much collaboration. The improvement is significant for CIGS but trivial in the CdTe area. For the new and emerging third-generation technologies, academics lead the research efforts and have show signs of rivaling world's leading innovators.

An investigation using patent data showed that the number of patents obtained by Chinese assignees skyrocketed since 2007, surpassing the total number of patents granted to all non-Chinese assignees combined. A similar rapidly rising trend is observed when looking at the number of solar-related patents granted to Chinese assignees in the U.S. although the actual number of patents is much smaller than that in China. Although the sheer number of patents suggests that China has improved its solar innovation capacity in the past decade, the fact that a much smaller number of solar PV patents was granted to Chinese entities the U.S., suggest that there is still a large room for quality improvement among Chinese patents. Further, an analysis of patent lapse rate shows that Chinese patents are less likely to renew and patents filed by Chinese academics have the highest lapse rate, indicating a lower patent quality.

Compared to where it stood 15 years ago, the Chinese solar PV innovation TIS subsystem has come a long way. However, it still lags in solar cell efficiency and patent quality in certain technologies compared to world's leading PV innovators. Innovation in China is often too incremental and not disruptive enough. The "catch up" mindset makes China comfortable to follow but lacks of the ambition to lead. The historical gap in scientific knowledge and methodology decides that China has to play a catch up game to certain extent, but the close tie between academics and the PV industry requires the former to be attentive to the latter's practical concerns for cost and commercializability reason, which confines their creativity.

The next section will discuss policy implications based on the findings. The implications are drawn from the study of the Chinese solar PV innovation system, but many of them have broader applications beyond country and industry boarders.

3.8.2. Policy Implications

First and foremost, the improvement in China's solar PV innovation strength benefited from having a national vision for PV innovation and the supporting policies that followed. The national vision legitimizes the status of solar PV innovation. It creates a friendly and certain environment for researchers, which in turn mobilizes talented people to devote their career to the field.

Secondly, although a national vision and supporting policies are necessary for innovation to happen, policymakers should refrain from offering technical guidance without thoroughly consulting the science and technology community as well as the industry. In other word, the job of setting research agenda details should be left to scientists and technologists, and the decisions to commercialize technologies should be informed by the industry and market trend. Granted, there is a fine line between where policymakers' "champion" role stops and the scientific and industrial communities' job starts, but the rule of thumb is that politicians and bureaucrats should not be doing their job. Instead of putting its hand on every step of innovation, nowadays, MOST emphasizes its role in the following areas:

1. Set strategic innovation visions. Use the visions to send policy signals to innovation players and the market. ***Influences their direction of search*** of innovation actors in the system by communicating clearly the priority area.
2. Build a public research platform to facilitate ***knowledge development and diffusion and develop positive externalities.*** A public research platform is a physical space, supported by public budget, where research can be conducted and shared across the scientific community.
3. Facilitate ***knowledge development and diffusion*** by supporting basic research that has significant impact on society and national economy and emerging technology research that could potentially turn into a game changer.

Thirdly, government innovation policies and programs should consider the entire lab-to-market spectrum. Conventional RDD&D program design links research with production and eventually the market, but it divides the continuous technology development process into artificial stages. It is often tricky to know where to draw the line between stages, as shown in the example of Chinese STI programs. A better approach would be to integrate the entire RDD&D cycle to reduce overlaps and minimize the inefficient use of resources. This would require more collaboration and better coordination among players from both academia and industries.

Fourthly, people are a valuable asset. An innovation system should not only be about technology, it should also be about people. An innovation system should foster its human capita by investing in education. Lessons from China showed how stop investing in education (cultural revolution) can leave a country with a huge knowledge gap that takes generations to overcome. So investing in education that promotes learning and creativity is necessary for innovation. However, in case of a historical knowledge gap, which many third world countries have, mechanisms should be put in place to leverage external resources to fill the gap. The Thousand-Talent program in China is an example of how active global recruitment of talented researchers brought knowledge that is not able to be draw endogenously from the system and produce significant advancement to the innovation system. In addition, knowledge and methodologies brought from the outside should not only be utilized, but also be codified into institutions such as the education system so that they generate long-term benefits.

Last but not least, a well-established information collection and management system coupled with good transparency and accountability is crucial for evidence-based policymaking. Its importance transcends disciplines. You cannot manage what you cannot measure. Collecting and allowing access to information and data is the foundation for good governance. Information on public R&D investment and its distribution and output by sector, by technology, by source and by recipient would allow policymakers to understand and enhance the effectiveness and efficiency of their policies. Opening up data and information to the public would also allow third party researchers and analysts to dissect the knowledge and possibly come up with ways to help design policies that are more effective and efficient. More openness will also lead to better accountability, which is always desirable.

CHAPTER 4.
THE SOLAR PV MANUFACTURING SYSTEM IN CHINA

4.1. Introduction

China, the world's largest energy consumer and carbon emitter, has made developing the clean energy industries one of its top priorities (National Economy and Commerce Commission, 2001; The 14th Session of the Standing Committee ofthe 10th National People's Congress, 2005). Solar energy is at the forefront of China's transition to clean energy economy. The solar energy industry in China has come a long way since its inception at the turn of the 21st century. Chinese solar PV installed capacity has grown rapidly since the passage of the Renewable Energy Law in 2006, reaching 7 GW annual installation in 2012 (Montgomery, 2013). In 2013, China installed close to 12 GW of PV capacity (BNEF, 2014a), surpassing Germany and the United States for the first time to become the world's largest PV installer. The figure was slightly lower in 2014, which was 10.6 GW, but it pushes the totally solar capacity of the country to 30GW (National Energy Agency, 2015). It is reported that in the first nine months in 2015, China added another 9.9 GW solar capacity to its fleet (National Energy Agency, 2015). The National Energy Agency, China's energy regulative body, announced in October 2015 that China had set a goal of 150 GW for 2020 (Xinhua News Agency, 2015a).

Behind the country's fast deployment of solar PV is China's world's largest PV manufacturing industry, which has grown from almost non-existent in early 2000s to account for 70% of the global solar PV production in 2014 (GTM Research, 2013). Today, has at least 65GW of solar module production capacity (PV-Tech, 2014). Seven out of the ten World's largest PV manufacturers in 2014 are Chinese (PV Tech, 2014).

China is tailor-made to become a significant global solar manufacturing player for environmental, social, economical, and technical reasons.

First, environmentally speaking, as a country plagued by heavy environmental pollution, China has an internal demand for clean energy like solar. The frequent off-the-chart PM2.5 readings in many Chinese cities have brought the air pollution crisis to the public attention. Heavy reliance on fossil fuel for winter heating and electricity consumption is the main reason for bad air quality. The public's demand for cleaner power sources as a solution to the air quality issue has never been higher. The situation calls for more solar deployment, which has to be supported by solar manufacturing.

Second, from an economic perspective, solar PV manufacturing is a good candidate for economic development. As a fast growing clean energy manufacturing industry, solar PV production checks almost all the boxes. It creates jobs, which is very much needed for a country that has 1.5 billion population. The large skilled labor pool also makes China suitable for this industry. It produces GDP and generates tax revenues; both are highly preferred for a country that is used to see double-digit economic growth. It makes products that many believe holds the promise to the world's energy future yet is not difficult to produce. For silicon-based solar PV, the most dominate type of commercial PV technology, the manufacturing processes can be broken into three parts: the preparation of poly-silicon is largely a chemical engineering process; the production of sola cells draw knowledge mostly from electronic engineering; finally the assembly of solar panel is a mechanical process. Figure 1. illustrates the process to produce a solar module. The point is that the steps required to transform raw materials eventually to a panel is small, compared to similar industries like the semi-conductor industry, or to other renewable energy technologies like wind turbine manufacturing. The knowledge required is well within the bound of China's manufacturing skillset. Finally, given the rising global demand for solar panels, the room to export solar panel made in China is large. This is also a preferred feature because China has built its rapid economic growth based on an export-oriented model, and its decision-makers have developed a taste for export-oriented industries. The ability to export products is not only a neat business strategy, it also give the solar manufacturing industry political cloud.

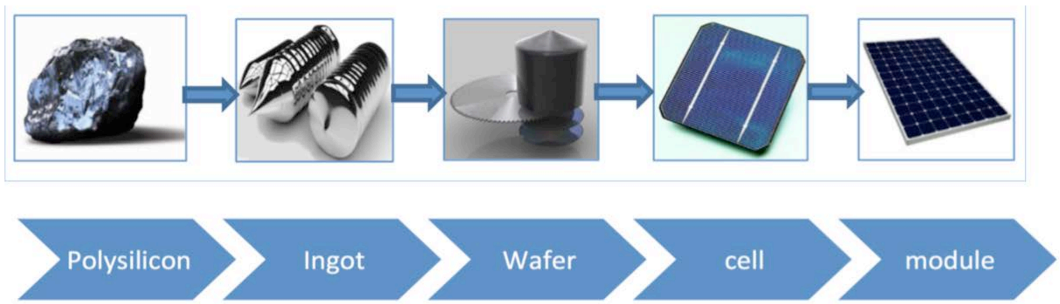

Figure 4.1 Silicon-based Solar PV Production Process

China's ability to quickly develop a global competitive solar PV industry has caught the world's attention, but it also puts the industry under scrutiny. Panels made in China are primarily known for its affordable price. Most of them have middle-of-the-road electricity conversion efficiency, an indicator that determines the amount of electricity generation from a panel and a key measure of the quality and performance of a panel. Complaints about the quality issues such as panel breakage, fast degradation rate, etc, about solar panels made in China were common in the late 2000s and early 2010s. Moreover, the rest of the world questions the real sources of Chinese manufacturing companies' cost competitiveness. Solar panel manufacturers from the U.S., European Union, Australia, Canada and India raised questions about Chinese companies' pricing practice and Chinese government's role in supporting the industry. They claimed that Chinese firms sell their products at prices below their production cost, which lead to the anti-dumping allegation. The Chinese government was also blamed for unjustifiably subsidizing the industry, which resulted in the countervailing allegation. In the E.U. and U.S. cases, Chinese companies were found liable to dumping and receiving unjustifiable government subsidies and are penalized by selling price floor and export quota imposed by E.U. and import duty imposed by the U.S.

Even though the punitive measures have been put in place for Chinese manufacturers, the debate about the real sources of their market competitive is far from settled. Many overseas companies who have their market share eaten by Chinese companies believe that the main reasons that Chinese firms have been able to do so is because they engage in unfair business practice such as dumping and they receive a lot of subsidies from the government which significantly lower their cost. Some economists and business strategists reference factors such as low labor and land cost, loose labor regulation as reasons why manufacturing industries flourish in China (Cheng & Stough, 2006; Zhou & Ma, 2000). The pollution haven hypothesis (Cole, 2004; M. S. Taylor, 2004) poised that loose environmental regulations attracts foreign direct investment from development countries where costs for environmental regulations are higher to developing countries where the cost of compliance is low. Empirical studies find that although environmental regulations have a mixed impact on multinational companies' offshoring decisions, they do have a sizable impact on company's manufacturing cost (Bommer, 1999; Dean, Lovely, & Wang, 2009; List, Millimet, Fredriksson, & McHone, 2003; Millimet & Roy, 2015). Some scholar found that the Chinese's ability to conduct re-design, re-engineering, and process innovation has given them a leg-up in lowering cost (Nahm & Steinfeld, 2014b). Finally recent studies have found that supply chain development and economies of scale might have contributed to the building of China's competitiveness in solar PV manufacturing (Goodrich, Powell, James, Woodhouse, & Buonassisi, 2013b). This chapter means to test these theories in both quantitative and qualitative fashion, to understand the real sources of China's solar PV manufacturing industry's comparative advantage and what they suggest about the industry and the global competition going forward.

Using a sample size of 7 Tier 1 Chinese solar PV manufacturers, based on a classification developed by Bloomberg New Energy Finance, this chapter will first quantitatively examines the causal links between low solar panel production cost and a suite of factors that represent economies of scale, subsidies, innovation, and production input using an approach called fuzzy set Qualitative Comparative Analysis (fs/QCA).

Many intangible factors, such as a country's business culture, its political economy structure, the interactions among players along the supply chain, etc., are difficult to be quantitatively measured. In addition, quantitative analysis of factors like government incentives and subsidies, the scale and functions of the supply chain, etc., albeit possible, is bounded by data availability and quality. However, these factors, along with a few others, are all important determinants that affect the overall competitiveness of the solar PV manufacturing industry. In order to fully understand the formation and maintenance of the competitiveness of the solar PV industry, Sector 3 of this chapter draw from the rich qualitative data this research has collected and apply them under the TIS framework to study both the tangible and intangible factors that are believed to have an impact on the competitiveness of the solar PV manufacturing subsystem.

4.2. Quantitative Analysis of the Sources of Competitiveness in the Solar PV Manufacturing Subsystem

4.2.1. Hypotheses

This research hypothesizes that three types of factors could affect the cost of producing solar PV.

First, government subsidies are one way to lower the cost of production, besides other public benefits that they provides such as improving on labor skills, infrastructure readiness and capital accessibility (Sanjaya Lall, 2004). Empirical evidence from both developed countries (Jacobsson, Andersson, & Bångens, 2002; Kern & Smith, 2008) and new industrialized economies (NIEs) has suggested that government subsidies play an important role in shaping demands, fostering supplies, and enabling the development of their infant industries (Ayoub & Yuji, 2012; C Freeman, 1987a; Hamilton & Biggart, 1988; S Lall, 2001; Sanjaya Lall, 1992; Lincoln & McBride, 1987).

There are many types of subsidies that are used by governments in both China and the U.S. They can be grouped into five categories: investment subsidy/grant, tax incentive, inputs subsidy, preferential lending, and infrastructure and social welfare contribution (Bayaliyev, Kalloz, & Robinson, 2011; Deutch & Steinfeld, 2013a; Sun, 2013). Both countries use all five types of subsidies to support their solar PV industry, but to different degrees. Types of subsidies used in China include corporate income tax exemptions/reductions, tax credits for R&D spending, low interest rate bank loans, grants for production capacity expansion, grants for workforce training/electric infrastructure upgrades and etc. (Bayaliyev et al., 2011; Deutch & Steinfeld, 2013b; Sun, 2013). In the U.S., there is a tendency to avoid, or at least be very careful with, issuing direct government handouts, like grants or loans. Tax incentives, however, are considered as less controversial and therefore, are more commonly used. Tax incentives for PV manufacturing in the U.S. include corporate income tax credits and manufacturing tax credits, and Investment Tax Credits for PV installation (Center for Resource Solutions, 2010; Deutch & Steinfeld, 2013b). There are some grants administered by the U.S. DOE's SunShot Initiative and Solar Energy Technology Program. They are issued as a form of award for innovation and cost reduction, usually through a competitive process (U.S. DOE SunShot Initiative, 2014). U.S. DOE and state government also provide loans and loan guarantees to solar PV manufacturers. They lower the barrier to access capital, although depending on whether there are also low-interest clauses attach to the loans, they may or may not directly lower the *cost* to use the capital. With the above information, this study hypothesizes the following,

Hypothesis 2. Subsidies lead to lower PV production cost.

Economies of scale are another driver for low-cost production. Economies of scale refer to the phenomenon that the cost per unit of production decrease at an increasing rate as the scale of operation expands. It gives firms with large production capacity a cost advantage because they are able to spread their fixed costs over a greater number of goods, as well as conducting bulk purchasing and marketing, and exercising bargaining power in negotiations to access lower-cost financing (Arrow, 1962; P.

Krugman, 1991b; Kwon, 1986; Pratten, 1971). When applied to the PV manufacturing context, the theory of economies of scale suggests that firms with higher production capacity have lower production cost.

Hypothesis 3. Larger production capacity leads to lower PV production cost.

Firms can also creates economies of scale through vertical integration, which allows them to internalize its supply chain to eliminate or reduce the transaction costs that would otherwise occur in dealing with external suppliers (Teece, 1980; Williamson, 2000). Studies have found that the PV manufacturing industry is going through a big wave of vertical integration, especially in China where a few large firms are expanding their footprint to both upstream supply industries and downstream business like PV station development (Neidlein, 2014). Empirical evidence suggests that there is a strong correlation between firms' vertical integration strategy and their low production cost (Grossman & Hart, 1986; Williamson, 1971).

Hypothesis 4. Vertical integration leads to lower PV production cost.

Last but not least, innovation has long been held at the core of long-term competitiveness of all business. Technological innovation does not equate invention of new products. Rather, it encompasses not only product invention, but also the research and development that enables better product design, higher product quality, higher resource utilization rate, less input material requirements, and easier manufacturing processes, all of which would increase a firm's competitiveness in marketplace. Although this competitiveness is often reflected in an increase of market share (Capon et. al. 1992) and better stock market performance (Chaney, Devinney, & Winer, 2014; Girotra, Terwiesch, & Ulrich, 2006); evidence is mixed in terms of whether corporate R&D leads to lower production cost. In fact, classical economic theory suggests that R&D spending will increase the production cost because it drives up the overall variable cost. However, if take the long-term impact and the knowledge spillover into consideration, the, investment into R&D activities could lower the production cost of a firm. Given the mixed evidence, this study uses author's insight about the industry and the qualitative information collected from the fieldwork to inform the formation of the hypothesis. Quantitative information about firm's R&D spending (Table 3.12 and Table 3.13 in Chapter 3) and company's solar panel selling price matches with the qualitative information collected from the fieldwork that companies with higher R&D investment faces higher selling prices, which infers higher production cost. Therefore, this study hypothesizes the following

Hypothesis 5. Firm-funded product innovation increases production cost.

4.2.2. Quantitative Research Method and Data

4.2.2.1. Fuzzy Set-Qualitative Comparative Analysis (fs/QCA) as A Research Method

This research attempts to quantitatively understand the causal factors leading to the low solar PV production cost among leading Chinese firms using Fuzzy set qualitative comparative analysis (fs/QCA).

Fuzzy set qualitative comparative analysis is a comparative approach that is fit to analyze the causal configurations of a set of variables that consistently appears or does not appear in order to produce certain outcome. It is based on the idea that causal relations are frequently better understood in terms of set-theoretic relations rather than correlations (Fiss, 2007; Ragin & Fiss, 2008; Ragin, 2000, 2008). It uses Boolean algebra to create algorithm to reduce numerous causal possibilities to a reduced set of configurations that lead to outcome (Fiss, 2011). The approach was introduced by Ragin (Ragin, 2014) and later extended (Ragin & Fiss, 2008; Ragin, 2000, 2008).

Fs/QCA is grounded in set theory that allows for a detailed analysis of how causal conditions contribute to a particular. Peer Fiss in his 2011 paper stated the strength of fs/QCA in the following way. "This approach is uniquely suited for analyzing causal processes because it is based on a configurational understanding of how causes combine to bring about outcomes. The basic intuition underlying QCA is that cases are best understood as configurations of attributes resembling overall types and that a comparison of cases can allow a researcher to strip away attributes that are unrelated to the outcome in question, in which one examines instances of the cause and outcome to understand patterns of causation" (Fiss, 2011). Since the goal of this study is exactly to understand under what causal conditions that firm can achieve a lower production cost, fs/QCA is perfectly suited for this work.

4.2.2.2. The Operationalization of fs/QCA

The internal calculation process of fs/QCA includes three steps. The first step is to list all possible combinations of the causal conditions in a data matrix known as a truth table. Assuming there are n causal variables, then the truth table should include 2^n rows. Each row of this table is associated with a specific combination of variables. After this theory construction, empirical cases are then matched to the rows of this truth table. Depending on the empirical values on these variables, some rows may contain multiple cases while some only a few; and it is entirely possible that some causal variable combinations have no matching cases.

The second step concerns limiting the potential solutions to a few highly possible ones by reducing the number of rows using two criteria: (1) the minimum number of cases required for a solution to be considered and (2) the minimum consistency level of a solution. "Consistency" in this case is defined as the degree to which cases correspond to the set-theoretic relationships expressed in a solution. Consistency can be estimated using the number of cases that match a given configuration of variables and at the same time exhibit the outcome (e.g. lower the PV production cost) divided by the number of cases that match the same configuration of variables but do not exhibit the outcome (e.g. does not lower the PV production cost).

In the final step, an algorithm based on Boolean algebra is used to logically reduce the truth table rows to simplified combinations. When using the fs/QCA pack software, the truth table algorithm is defaulted to the one developed by Ragin (2005, 2008), based on a counterfactual analysis of causal conditions. Counterfactual analysis is useful to fs/QCA analysis because it helps alleviate the problem with having too few empirical cases for a too large amount of possible variable configurations. One can imagine that in the process of determining the possible causal configurations, even a small number of variables can quickly lead to a huge number of truth table rows. Yet, researchers are usually confined by the limited number of empirical cases that they have to fit the truth table. Fortunately, counterfactual analysis offers a way to overcome the limitations of a lack of empirical instances.

To begin with, the truth table algorithm of counterfactual analysis gives two set of solutions: the parsimonious and the intermediate solutions based on “easy” and “difficult” counterfactuals, respectively (Ragin 2008). “Easy” counterfactuals refer to situations where a redundant causal condition is added to a set of causal conditions that by themselves already lead to the outcome in question. If either the presence or the absence of a particular variable would still lead to the outcome, holding the rest of the configuration constant, then the addition of that variable does not make a difference. In other word, an easy counterfactual works when adding another causal condition does not affect the outcome and therefore, the simplified solution is preferred.

“Difficult” counterfactuals are more complex, hence the expression. Unlike easy counterfactuals, which test the addition of one more multiple variables, difficult counterfactuals examine whether the removal of a set of causal conditions/variables leading to an outcome, assuming these variables are redundant. Unless empirical and theoretical evidence both suggest the additional causal condition is irrelevant to the outcome, which is rare, it is risky to drop the condition in order to reduce the solution to a simplified form.

Two sets of solutions will be developed based on the two types of counterfactual analysis: Parsimonious solution includes all simplified variable causal configurations regardless of whether they are based on easy or difficult counterfactuals. In contrast, intermediate solution only includes the simplified ones based on easy counterfactuals. In the fs/QCA world, causal conditions that belong to both parsimonious and intermediate solutions are deemed as core configuration, whereas peripheral configurations include those that appear in the intermediate solution but are eliminated in the parsimonious solution. The difference between core and peripheral conditions is the strength of the evidence relative to the outcome. In other word, core configurations are more causally likely to explain the outcome (Fiss, 2011).

4.2.2.3. Variables and Data

The cost of production is the outcome that needs to be explained. Three types of explanatory variables will be used. According to Hypothesis 2, a vector of variables that measure subsidies will be included in the fs/QCA analysis. Given the data availability, this study focuses only on capital subsidies that may result in lower cost to access capital and tax credits/exemption which lead to lower effective tax rates. Hypotheses H3 and H4 suggest explanatory variables in the fs/QCA analysis should also include measures of economies of scale such as manufacturing capacity, actual PV cell and module production, and degree of vertical integration. Last but not lease, firm level R&D spending will be used as a measure for innovation. Besides the explanatory variables, a set of control variables will be used to control for variances in production input factors like labor productivity and electricity.

As introduced in the Chapter 2, data used in this study come from Bloomberg Industries (BI)'s solar industry database, known as BI SOLAR (Bloomberg Finance L.P., 2014a). As the end of 2014, 13 solar PV module producers were classified as Tier 1 producers in BI SOLAR. Among the 13 PV module producers, 11 of them report information on production cost, manufacturing capacity and production, which are three crucial variables to this study and 9 out of the 11 firms are Chinese. As a result, these 9 companies make up the data sample for this dissertation

Table 4.1 summarizes the key statistics of the 9 PV module manufacturing firms that comprise the sample of this study. Each firm is considered as one case. Although fs/QCA does not explicitly deal with time series, this study treats each quarter as an independent QCA analysis. As a result, 22 separate QCA analyses were done using 22 quarterly datasets.

Hypotheses proposed in earlier chapter lead to the following causal model

Production Cost ~ Subsidies * Economies of Scale * Innovation * Production inputs

Table 4.1 PV Manufacturing Companies Considered in This Study

Company Name	Country of Production	2014 Production as % of world total	Year Went Public	Stock Trading Venue	Founder
Trina Solar	China	7.60%	2006	NYSE	Entrepreneur
Yingli Green Energy	China	6.90%	2007	NYSE	Entrepreneur
Canadian Solar	China	5.80%	2006	NASDAQ	Entrepreneur
Hanwha SolarOne	China	5.30%	2006	NASDAQ	SOE Spinoff/ conglomerate subsidiary
JinkoSolar	China	5.00%	2010	NYSE	Entrepreneur
JA Solar	China	5.00%	2006	NASDAQ	SOE Spinoff /Join venture
ReneSola	China	4.10%	2006	NYSE	Entrepreneur
LDK Solar	China	0.60%	2007	NYSE	Join venture/ Entrepreneur
Suntech Power	China	5.8%*	2006	NYSE	Entrepreneur
Total		46.4%*			

Source: Bloomberg BISOLAR database.
* Suntech's market share is calculated based on 2011 data, the year before Suntech defaulted on its investor's bonds. Total market share does not include Suntech.

Table 4.2 provides a summary of the variables. Based on set-theory and Boolean algebra, fs/QCA requires variables to be on a 0-1 scale, where 0 represents complete absence of the variable and 1 represents the complete presence. As show in Table 4.2, most variables used in this study do not come naturally on a 0-1 scale. Therefore, they need to be transformed, or in the fs/QCA language "calibrated" to be QCA ready.

Calibration is essentially a process of benchmarking the values of a given variable across cases. The calibrated values indicate each case's relative position in relationship to each other. For example, in this study companies' production costs in each given quarter are benchmarked according to the highest cost of that quarter. The highest cost is assigned the value of 1, which means it represents the fully presence of high production cost. All the other companies' production costs are then benchmarked to the highest cost and take on values that are a fraction of 1. Once the transformations are done to all variables in all quarters, they become the empirical data inputs to the fs/QCA software package. The software will then calculate the fuzzy score for all cases (companies) in each variable based on the empirical data inputs and three assigned anchors: the 95 percentile value (cutoff for full membership), the 50 percentile value (cross-over point), and the 5 percentile value, (cutoff for full non-membership). The software will then compute a truth table showing all the possible causal combinations of variables. The next step is for the researcher to make a judgment call as to what are the acceptable levels of case frequency and causal pathway consistency. Due to the small-N nature of this study, the case frequency was set at 2, which means at least 2 cases have to be present in order for a causal configuration to be passed on to the next analytical step. The minimum consistency was set at 75%, as recommended by the literature.

Table 4.2 Summary of Variables

Variable	Definition	Unit	Type	QCA Transformation
Dependent Variables				
Production Cost	Cost of goods sold of solar PV in a given quarter	$/W	Continuous	As a % of the highest cost

Table 4.2 Continued

Explanatory Variables – Subsidies				
Variable	Definition	Unit	Type	QCA Transformation
Cost of Debt	The effective rate that a company pays on its current debt in a given quarter	%	Continuous	As a % of the highest cost
Cost of Equity	The rate of return a firm pays to its equity investors in a given quarter	%	Continuous	As a % of the highest cost
Effective Tax Rate	Total tax paid over pre-tax income in a given quarter	%	Continuous	As a % of the tax rate range
Explanatory Variables – Economies of Scale				
Capacity	The possible output of a firm in a given quarter	MW	Continuous	As a % of the largest capacity
Vertical Integration	The level to which a firm internalizes the upstream and downstream processes into its own operation	N.A.	Discrete	As a % of full integration level
Explanatory Variable – Innovation				
R&D Spending	Corporate R&D spending as a percentage of corporate revenue	%	Continuous	As a % of the highest spending
Explanatory Variable – Production Input				
Electricity Rate	Average electricity price paid in a given quarter	$/kWh	Continuous	As a % of the highest cost

4.2.3. Results

Table 4.3 and 4.4 show the results of the pre-2010 era and post-2010 era. In the pre-2010 era, the co-appearance of low electricity cost, low R&D investment, low cost of debt and low cost equity lead to lower solar panel production costs among Chinese players. The impact of vertical integration, module capacity and tax rate are mixed and there are no consistent pattern among these three variables and between them and the rest of the four variables that lead to low PV production cost. However, in the post-2010 era, the higher level of vertical integration consistently co-exist with the four variables identified in the pre-2010 era as factors that cause low production cost. Even though the evidence on module capacity in the same era is not as consistent as the other five variables, there is no contradicting trend regarding module capacity. In other word, the presence of large module capacity, in combination of low electricity cost, low R&D investment, low cost of debt and low cost equity, leads to low solar panel production cost, although in a few large module capacity has a neutral relationship with low PV production cost, meaning neither the presence or the absence of large module capacity matters. There is still no clear pattern regarding the level of tax rate's causal relationship with low production cost.

One explanation as to why the patterns are different before and after 2010 is that, the economies of scale production of the Chinese PV companies only started to form since 2010. Before that period, companies all operated at a small scale. The fact that vertical integration and module capacity become meaningful causal factors for low cost production only after the economies of scale was formed suggests that there is a tipping point for manufacturing scale's impact on production cost.

Table 4.3 Pre-2010 fs/QCA Results

	Electricity	R&D%	Cost of debt	Cost of equity	Vertical integration	Module capacity	Tax rate
2010 Q1	↓	↓	↓	↓	↑	?	?
2009 Q4	↓	↓	↓	↓	<↑>	↑	<↓>
2009 Q3	↓	↓	↓	↓	<↑>	↑	<↓>
2009 Q2	↓	↓	↓	↓	?	?	?
2009 Q1	↓	↓	↓	↓	<↑>	<↓>	?
2008 Q4	↓	↓	↓	↓	?	<↓>	<↓>
2008 Q2	↓	↓	↓	↓	?	?	□
2008 Q1	↓	↓	↓	↓	?	□	?
Summary	↓	↓	↓	↓	□	?	?

Notes :

↓ means the closer to 0 the variable is, the more likely it leads to lower production cost.
↑ means the closer to 1 the variable is, the more likely it leads to lower production cost.
<↑> or <↓> means 2 possible causal paths, one being ↑ or ↓ and the other being neutral.
/ means neutral.
? means two opposing causal paths.

Table 4.4 Post 2010 Results

	Electricity	R&D%	Cost of debt	Cost of equity	Vertical integration	Module capacity	Tax rate
2013 Q3	↓	↓	↓	↓	↑	↑	/
2013 Q2	↓	↓	↓	↓	↑	↑	↓
2013 Q1	↓	↓	↓	↓	↑	↑	/
2012 Q4	↓	↓	↓	↓	↑	↑	↑
2012 Q3	↓	↓	↓	↓	↑	↑	/
2012 Q2	↓	↓	↓	↓	↑	<↑>	<↑>
2012 Q1	↓	↓	↓	↓	↑	↑	↑
2011 Q4	↓	↓	↓	↓	↑	↑	/
2011 Q3	↓	↓	↓	↓	↑	/	↓
20112Q1	↓	↓	↓	↓	↑	<↑>	<↑>
2011 Q1	↓	↓	↓	↓	↑	/	↑
2010 Q4	↓	↓	↓	↓	↑	/	↓
2010 Q3	↓	↓	↓	↓	↑	<↑>	<↓>
2010 Q2	↓	↓	↓	↓	↑	<↑>	<↑>
Summary	↓	↓	↓	↓	↑	Pro ↑	Mixed

Notes :
↓ means the closer to 0 the variable is, the more likely it leads to lower production cost.
↑ means the closer to 1 the variable is, the more likely it leads to lower production cost.
<↑> or <↓> means 2 possible causal paths, one being ↑ or ↓ and the other being neutral.
/ means neutral.
? means two opposing causal paths.

4.2.4. Discussion of the fs/QCA results

Therefore, hypothesis 2 cannot be rejected based on the finding about cost of debt and cost of equity. The lower level of cost of debt and cost of equity suggest the existence of government subsidies, and they are causally related to lower panel production cost.

Effective tax rate is another area that government subsidies could affect the production cost. However, there is no consistent evidence that lower tax rate leads to lower production cost.

Evidence on hypothesis 3 and 4 is mixed. It is found that module manufacturing capacity expansion and vertical integration could decrease the production cost of Chinese and only when they reach certain scale. The Chinese manufacturing capacity reached economies of scale around 2009 to 2010 (Figure 4.2). Before 2010, the capacity expansion and vertical integration do not have a consistent effect on production cost because the production had not reached a critical mass. However, the tipping point came in 2010, where the solar PV production capacity reached the economies of scale. Since 2010, strong evidence shows that they drive down the cost of production. The evidence suggests that economies of scale is not an abstract concept. Rather it has to be backed up with real at-scale production (as seen in the production capacity growth in 2010) in order to realize its impact on production cost reduction.

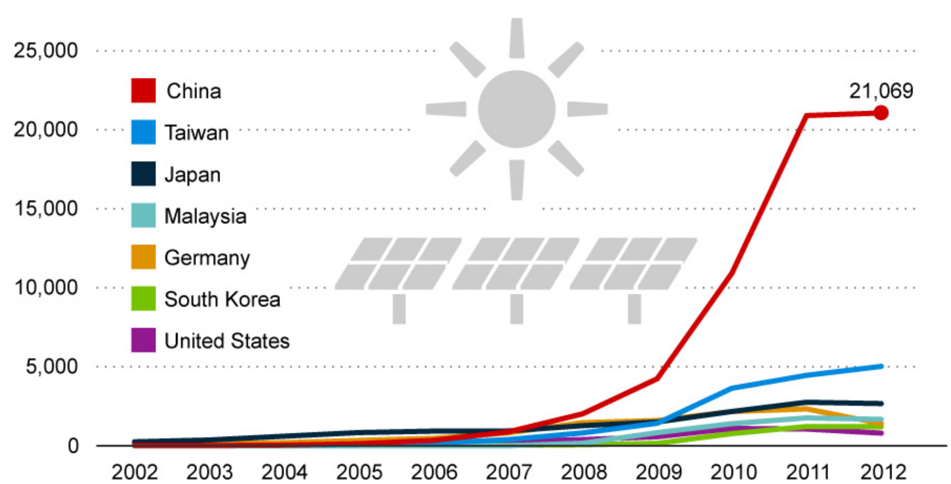

Figure 4.2 Annual Solar PV Production by Country (MW)
Source: Earth Policy Institute

Corporate spending on R&D activities turns out to increase manufacturing cost. The same result is true regardless of using R&D spending of the current term or 2 year cumulative R&D spending as the measure. As a result, hypothesis 5 is rejected.

Due to data availability, a few factors that are believed to also have impact on PV cost production are not included in the models presented in this paper. These factors include subsidy measures such as free cash grants and land subsidies; economies of scale measures such as the level of clustering and agglomeration; innovation measure like process innovation; and production input measures such as cost of labor.

It is important to realize that in spite of the insights that these models offer, statistical analysis is bounded by the quality and span of the dataset. Instead of treating the statistical analysis in isolation and taking the results that they generate as the final verdict, a more sensible approach is to combine statistical analysis results with on-the-ground understanding of the industry. This study strives to do the latter by conducting a rigorous analysis based on extensive interviews with Chinese and American solar PV Industry executives, PV technology R&D personnel, government officials and policymakers, and industry organizations. Interview data on China were collected during five research trips to China (three out of the five trips were conducted as part of the Stanford China Solar Project Team) where the author conducted 124 interviews with 109 individuals from four solar PV related fields: manufacturing, technology R&D, PV deployment, and policymaking/consulting/industry association, attended 2 academic conferences and 2 trade show, and took 28 site visits to 16 silicon, solar cell, solar module, and manufacturing tooling production plants and 9 site visits to 9 different PV research labs, 2 visit to industrial parks, and 3 site visits to distributed solar PV deployment sites. The methodology section of his work includes more details. Information collected from these activities is an enormously valuable resource that provides lots of insights regarding the sources of manufacturing competitiveness in China. The next section will develop a typology of potential sources of a manufacturing industry's competitiveness based on qualitative data and use it to dissect the strengths and weaknesses of the solar PV manufacturing subsystem in China.

4.3. Qualitative Analysis: Sources of Competitiveness of the Solar PV Manufacturing Subsystem in China

Factors that explain the source of competitiveness of the solar PV manufacturing industry spread across five dimensions as show in Table 4.5. This section will examine each factor using the TIS framework, explain their functionality and the mechanisms through which they contribute to or block the development of the solar PV TIS in China, especially the manufacturing subsystem.

Table 4.5. Determinates of Solar PV Manufacturing Competitiveness

Agglomeration Economies	Firm Strategy	Cultural	Resource	Policy
Economies of scale	Flexibility	Work ethic	Low cost skilled labor	National Industrialization Strategy
Complete, local, clustered supply chain	Process innovation	Pragmatic culture	Ready Infrastructure	Government subsidies and incentives
	Management	Desire to lower cost	Easy access to capital	PV Deployment policies
				Loose labor and environmental regulation

4.3.1. Agglomeration Economies Factors

Agglomeration economies are found by this study to be a big contributing factor to China's low cost production of solar panels. Agglomerations, stemming from economies of scale, industrial clusters, and network theory (Glaeser 2010; Krugman 1991), offer a region, an industry or even a firm multiple layers of benefits, including transportation, communication, market power, etc. The following subsections explore the ways in which the solar PV industry in China establishes agglomeration economies and uses them for its own advantage.

4.3.1.1. Economies of Scale

Economies of scale are the benefits associated with the size of production. It refers to the phenomenon that the cost per unit of production decreases at an increasing rate as the scale of operation expands. It gives firms with large production capacity a cost advantages because they are able to spread their fixed costs over a greater number of goods, as well as conducting bulk purchasing and marketing, and exercising bargaining power in negotiations to access lower-cost financing (Arrow, 1962; P. Krugman, 1991b; Kwon, 1986; Pratten, 1971). When applied to the PV manufacturing context, the theory of economies of scale suggests that firms with larger production capacity have lower production cost. Quantitative analysis shown in Section 4.2 of this chapter found that when firms' production capacities reach a critical mass, economies of scale would lead to lower solar panel production cost.

The solar PV industry in China uses economies of scale to its advantage. Since the 10th FYP in 2000, the central government started to promote the industrialization of the PV manufacturing industry through "economies of scale" development. The total solar cell manufacturing capacity grew from almost non-exist in 2000, to 500MW in 2005, to 8.9 GW in 2010, and eventually in 47 GW in 2014 and the actual production was 33 GW in the same year. During this process of building economies of scale, a great deal of policy, financial, and human resources were mobilized (***resource mobilization***). As the theory predicts, the manufacturing cost declined accordingly. Average cell selling price among tier 1 Chinese producers declined by 91% between 2005 and 2014 (Bloomberg Finance L.P., 2014b). During the same time period, the price of solar PV made by American manufacturer declined by only 50% (Bloomberg Finance L.P., 2014b).

The key link between manufacturing capacity expansion and the creation of economies of scale is that the former provide opportunities to Chinese manufacturers to take productivity and quality improvement of their production lines to a whole new level. Interviews with multiple Chinese PV manufacturers showed that every time they build a new factory or add additional production lines to an existing factory, they adopt new versions of manufacturing equipment and materials[26]. Newer materials and equipment are either cheaper or better than the older versions, and often times both. Newer equipment is usually more automated than older ones, reduce the need for manual labor and in turn lower the labor cost. Newer equipment also does better in stability, reliability, and precision measures, which means they produce better quality PV panels. Similarly, new materials that are adopted in new production lines during a capacity expansion would also allow solar cell efficiency improvement and increase product quality. Lastly, newer equipment is also likely to have bigger capacity (i.e. move from 25MW capacity per line to 30MW or 35MW capacity per line) so that the same number of workers would produce more panels[27]. The improvement in productivity leads to cost shaving.

Driving mechanism 4.1: Continuous capacity expansion allowed Chinese manufacturers to create economies of scale, during which process the manufacturers kept upgrading their production lines with better equipment and high quality materials, which led to higher productivity and lower cost.

One can feel startling differences between the production lines of a company that routinely goes through capacity expansion and one that does not just by talking a walk at the workshops. During a visit to Jiaxing, Zhejiang Province, we visited one Chinese factory and one American factory. The Chinese factory is the main solar cell production base of a Tier 1 company, the capacity of which grew from 600MW in 2010 to 2GW in 2014 while the price of their cell fell from \$1.17/W to \$0.24/W during the same time

[26] Interviewee #71, #72, #89, #97, #99, #104
[27] Interviewee #104

period. The building where the cell and module production workshops were located looked new and well maintained the work area was spacious and well lit, the level of automation was high, and the production line workers were mostly machine operators whose job looked routine but not intense. In contrast, the American factory has only 45MW capacity and it was located in a small old building. One striking observation about this American cell producer's facility was how labor intensive it is. Unlike the next-door Chinese facility, the American factory workshop was packed with workers who work intensely around the clock to perform their tasks. Considering it was essentially the same manufacturing process between these two factories, the American facility's level of automation was noticeably lower, which inevitably lows its productivity and consequently increases the unit production cost and hurts its market competitiveness. As of Q4 of 2014, the production facility of the American company had not expanded it capacity yet since it opened its door in 2011, which means it had been locked in the 2011-vintage manufacturing technology for at least 3 years while the Chinese factory went through at least one round of capacity expansion accommodated with tooling upgrade.

Both theory and empirical evidence supports the idea that economies of scale create cost advantage at the firm level. The comparison between the Chinese factory and the American-owned factory in the same city showed that Chinese companies' cost advantage does not simply come from the fact that they are located in China. Rather, the ability to continuously expand the manufacturing capacity offers a suite of cost reduction opportunities.

4.3.1.2. Supply Chain

In his seminal paper, Krugman used economic model to demonstrate the increasing return to high-density economic geographies (Krugman 1991a). He found that regions have a cluster of manufacturing activities to start with are likely to attract more similar manufacturing firms because of the existing large share of demand for similar supplies and the suppliers and infrastructures to fulfill the demand. The concept of "economies of agglomeration" or "clustering" is well documented in economics and urban development literature (N. Coe, Kelly, & Yeung, 2007; Ellison, Glaeser, & Kerr, 2007; Ellison & Glaeser, 1999; Fujita & Thisse, 2013; Gordon & McCann, 2000; Head, Ries, & Swenson, 1995). The idea is that firms could increase their marginal return through locating close to peers of similar kind or close to their upstream supplier or downstream consumers. The increasing return on economies comes from sources such as the ability to save on transportation cost, share common labor pool and infrastructure, and the knowledge spillover.

The Chinese solar PV industry is a living testimony of the clustering theory. The emergence and rapid development of the supply chain cluster in the Yangtz river delta area in China demonstrated how a dense supply chain cluster can provide an environment for ***entrepreneurial experimentation, resource mobilization, market creation, knowledge development and diffusion, creating positive externalities***, and eventually ***legitimize*** and strengthen the industry. Chapter 5 of this dissertation is dedicated to study the role played by supply chain in the development of the PV industry in China.

4.3.2. Firm Strategy Factors

Firm strategies are firms' response to market conditions given their resources and constrains imposed by the environment they embedded in. This study discovers that on the one hand, large Chinese PV companies operate just like any other publicly traded multinational in a sense that they use modern business management approaches in their day-to-day operation. However, this is a departure from the traditional experience-based management style that is common among many Chinese companies. On the other hand, the leading Chinese PV companies studied in this dissertation differ from their western competitors in their pursuit of low cost manufacturing via process innovation and working with a large number of local supplies.

Besides studying large Chinese PV manufactures, it is also crucial to stress the role played by small and medium enterprises (SMEs), and how their firm strategies shape the course of the solar PV industry in China. They are instrumental in the creation and maintaining of the cost advantage of the PV manufacturing industry in China.

4.3.2.1. Flexibility

Flexibility in manufacturing means the production system's ability to react and adapt to internal and external changes relatively easily and swiftly without incurring high cost (Chan & Chan, 2010; Fohrholz & Gronau, 2011).

The Chinese PV manufacturing industry has a relatively flexible and adaptable supply chain. It started with entrepreneurial PV producing companies and their SME supplier with diverse backgrounds. The rapid global PV market expansion combined with favorable government industrial policy ***mobilized*** a great deal of ***resources.*** Section 5.2 in Chapter 5 will give a full account of the history of supply chain development, but the ***entrepreneurial spirit*** allows the suppliers to use their respective specialties to carve out a market niche that suits their expertise. For example, the engineering background of Suntech's former CEO allowed the company to excel in product quality and led its Chinese peers in innovation. CGL-Poly's leading position in silicon processing, which is a capital and knowledge intensive sector, benefited from its parent company's ties to Ministry of Defense's R&D budge. Unlike large companies represented by the previous two examples, the PV industry in China is made of a large number of SMEs with various backgrounds and they entered the sector with their own specialties. The supply chain section described how non-solar specific suppliers transferred their specialties developed for other industries to serve the solar PV industry. This flexibility on the supplier's side made the initial rapid development of the industry and its supply chain possible.

The suppliers' flexibility and adaptability continued to be an important factor as PV manufacturers' need for supplies became faster, more diverse, and more sensitive to cost. Because the suppliers in China were flexible to begin with, they are able to keep up with PV manufacturer's fast evolving demand. This is crucial in terms of realizing the cell and module innovation that PV producers designed in their labs, as well as achieving the cost-shedding goals set by PV producers. As said the deputy director of the 48th Research Institute

" Any new product design by PV manufactures' R&D teams will remain in their labs until material and tooling suppliers can come up with matching tools and parts to realize it in mass production."[28]

It highlights the often-overlooked importance of suppliers in ***knowledge development and diffusion***. They are instrumental in bring innovations from blueprint to reality. The flexibility demonstrated by suppliers in China in terms of modifying their old products or design new products to meet PV manufacturer' new product design or cost reduction goals has certainly enabled innovation and especially the rapid cost reduction observed in the industry in the past decade.

An important aspect of being flexible is the ability to quickly responding to change. Conveniently, things usually move fast in China. When encountered by a large order, Chinese PV manufacturers and suppliers can ramp up their production quickly by adding more hours and shifts to their workers without incurring a high cost. In cases of capacity expansion, the Chinese have the advantage of building a new factory at a speed faster than it is in many other countries. This is not just a function of laying the bricks in a faster speed. Rather, ready infrastructure and fast administrative approval process are also key to enabling flexibility. Three-decade long experience with building industrial park created a well-practiced system to facilitate industrial development. In well-run industrial parks, standardized factory workshop, electricity connection, and workforce training programs are available for new factories to utilize as soon as they move in[29].

[28] Interviewee #104
[29] Interviewee # 90

Even in the absence of industrial parks, the speed of building electricity grid, factory space, and other types of infrastructure is relatively fast because of the pro-industry administrative mindset and the convenience associated with publicly owned land.

Driving mechanism 4.2: Flexibility in the tooling and material supply chain enabled a short product lab-to-production line cycle. Flexibility in infrastructure supply made it easy and quick to bring on new production capacity. Both lower transaction costs and allowed companies to be agile and adaptable.

Besides the flexibility resides in the supply chain and the macro-factors related to running PV production factories, at the micro-level, Chinese companies also demonstrate efforts to stay flexible and therefore, competitive. One paradox is that automation can significantly increase productivity but it sacrifices flexibility. Human are infinitely flexible, but machines are not. Human can observe, assess, analyze, and adjust. In short, human can learn; yet machines can only do so to the extent that their operators is capable of doing. As a result, higher level of automation, as productivity-enhancing as it can be, reduces the amount of flexibility that a production process could have and it could have serious cost and product quality consequences. For example, in a highly automated production line, a breakdown of a single part at an early step can bring the entire production process to halt. A few practices were observed during factory tours conducted by the author in China.

At the solar cell production line of a tier 1 Chinese company, an additional mechanical arm was added to a testing machine to ensure that in situations where the solar cell transportation belt is halted, this additional mechanical arm can bring cells from elsewhere to keep the testing machine occupied. If it were not for the additional mechanical arm, the testing machine would have to be paused when the transportation belt ceases to work; but with the arm, the downtime is avoided and the productivity of the line is higher than it otherwise would be, which indirectly lowers the production cost. In module (not cell) manufacturing stage, Chinese companies in general deploys more manual labor partly because it requires less precious, partly because the value of modules are significantly higher than cells, which means a botched batch of product would inflect greater cost on companies. By using more people instead of machines for module assembly, manufacturers essentially put in many check points throughout the production process in order to avoid mass mid-produce.

4.3.2.2. Learning and Process Innovation

Learning by doing refers to the fact that knowledge grows over time as individuals constantly engage in a particular type of practice. Its primary function is ***knowledge development and diffusion.*** The acquisition of knowledge constitutes "learning" and learning is a product of experience. Learning is associated with repetition of certain type of performance. In the solar PV manufacturing context, as a assembly line worker repeats the same operation for a long period of time, his or her proficiency improves and the time required to finish the same amount of work decrease and hence, the cost of production decreases as a result of higher labor productivity. In explaining how experience leads to economies of scale, Arrow pointed out in his seminal piece about learning that "favorable responses [to problems emerged during manufacturing processes] are selected over time" (Arrow, 1962). The essence of his argument is that it is not only the repetitive nature of doing the same thing leads to productivity gain, it is also the purposefully selection of best work routines that improves the productivity. Similarly, Frederick Winslow Taylor in his study of scientific management illustrated how productivity increases and cost decreases through constant experimentations in order to find the "optimal" allocation of man power (Taylor 1911).

Literature has documented how things like internal manufacturing processes improvements, discovery of new tools and devices, as well as customer based re-engineering can lead to less input requirements, lower idol time, higher labor productivity and lower production cost (W. M. Cohen & Levinthal, 1990; Cohen, W. M., & Levin, 2007; C Freeman, 1987b). The term “process innovation” is used to describe such phenomena.

Unlike product innovation, process innovation has a murkier but also more encompassing definition. It refers to improvements of internal production processes, and discovery of new tools, devices and knowledge as well as customer based re-engineering. It is inseparable with learning and requires human ingenuity combined with experimental spirit, knowledge, and creativity (Arrow, 1962; Bengt Åke Lundvall, 2007; R R Nelson & Winter, 2009).Process innovation can lead to higher product quality, higher labor productivity, less inputs requirement, lower production cost, and any combination of these outcomes (Cohen & Levinthal, 1990; Cohen, W. M., & Levin, 2007; Freeman, 1987). There is a tendency in literature and in day-to-day thinking to overlook process innovation, or considered it not as important as “hardcore” product innovation. As Lundvall pointed out, this bias needs to be overcome because product and process innovation are interrelated, and latter is crucial to the former (Lundvall, 2007). Scholars also found that process innovation can be a significant source of firm competitiveness, which gives process innovation additional significance (Li, Liu, & Ren, 2006; Nahm & Steinfeld, 2014; Yam et. al., 2004).

The Chinese manufacturing industry did not pioneer process innovation, but it has been able to use it for its greatest advantage. Evidence from both the Chinese manufacturing industry in general (Breznitz & Murphree, 2011; Li et al., 2006; Yam et al., 2004) and its energy technology manufacturing industries in particular (Bullis, 2011; de la Tour et al., 2011; K. S. Gallagher, 2014; Lewis, 2013; Luo, 2013; Nahm & Steinfeld, 2014a) shows that China excels in conducting process innovation, which gives Chinese manufacturers an unique advantage over their foreign competitors.

Interviews with CTOs from tier 1 Chinese PV and wafer producers show that Chinese companies leverage the power of process innovation significantly[30]. Yingli's On-line research program and Trina's Golden Line innovation are such examples. The On-line research program is referred to as the "grass root innovation" program at Yingli. It means to optimize production efficiency at factory floor by mobilizing production line workers to contribute their ideas and best practices that developed from daily work ***(resource mobilization)***. Just like the slogan of the research program says, "Everyone is an innovator." the program aims to tap into the low-cost, handy ways possessed by workers to improve production line performance and reduce production costs. One successful example coming out of the program is the reengineering of wire saw by a wire saw operator to cut wafers thinner and in a more uniformed way. It increased wafer yield and improved the efficiency of solar cells (thinner wafer results in lower electric resistance and therefore, higher efficiency). This process innovation does not fundamentally change the wire saw designed, but by adding a few minor tweaks to the machine it leads to higher product quality and allegedly can save over one million dollars in production cost every year[31]. In a way, the On-line research program is complementary to the science-based research that happens at Yingli's State Key Lab.

The Golden Line program at Trina is an intermediate step linking the research conducted at the State Key Lab with mass production. Typically, solar cells suffer efficiency losses when they are transferred from research labs to production lines. The goal of the Golden Line program is to ensure the most efficient "lab to production line" transition through a pilot production line where test production is carried out in conjunction with simulation, feedback, re-innovation, and re-engineering. It is reported by the company that products came out of the Golden Line can achieve a 0.6% efficiency gain and a 7.4W to 10.5W module power output gain in actual mass production.

[30] Interviewee #31, #46, #53
[31] Interviewee #31

Another example comes from GCL Poly. By reconfigure the equipment arrangement on the factory floor, GCL was able to cut the material transportation time and reduce the number of workers required on the production, which eventually lowered the cost of production.

The mechanical arm example given in the last section is another example. Examples of cost-reducing process innovation in Chinese solar PV factories are ample, and Chinese companies are certainly proud of these low-key yet practical innovations because they further the companies' cost advantage at a minimal cost.

Driving mechanism 4.3: Process innovations stemming from work experience and daily practice on production lines optimized the production process at little cost. They increased productivity and lowered cost.

4.3.2.3. Management

The adoption of modern business management method has been on the rise among large Chinese companies and is credited for improving product quality and the overall business performance[32]. Having a management principle is important to Chinese companies that have global ambitions, because for a long time, Chinese manufacturing industries rely on advantages in labor supply, natural resources, and lax regulation. Yet, business management was based primarily on experience rather than on scientific principles. As manufacturing industries in China eager to transition to the higher value-added part of the global production network while maintaining their cost competitiveness, they all realize that efficient management of their entire production process is key. For leading Chinese solar PV makers, the traditional experience-based management method no longer fits their image and their relative position in the industry. For all intents and purposes, Chinese companies need a modern management brand to ***legitimate*** their position as industry leaders.

[32] Interviewee #57, #58, #71, #88, #89.

Among all the modern management schools, delicacy management is the most popular among Chinese PV manufacturing companies. Delicacy management stemmed from three fields: scientific management founded by Frederic Taylor (Taylor 1911), production quality control principles originated from W. Edward Deming (Deming, 1986), and the Toyota Production System (Ōno, 1988; Roos, Womack, & Jones, 1990; Shingo & Dillon, 1989; Womack, Jones, & Roos, 1991). It was spearheaded by Japanese carmaker Toyota, and has a huge amount of following in China (Shu-qin, 2010; Xu, Lu, Shi, Wang, & Peng, 2010; Xueying, 2011).

Delicacy management requires managers to turn abstract business strategies into specific production or operational goals, break them down to executable and assessable tasks, and monitor and evaluate the implementation of the tasks on a timely manner (usually daily). It demands a high level of division of labor with skilled and motivated workers at each step of the production process to accomplish the tasks. Under delicacy management, the input and output of each production process is standardized and quantified. It is through the attention to details at every single production step, delicacy management strives to improve product quality and reduce production cost. Furthermore, instead of treating each worker and production process as an isolated unit, delicacy management calls for a systematic approach. In other word, the approach values the optimization of the entire production process because at the end of the day, it is the totality of all the production steps that decides the performance of a factory.

In addition, delicacy management requires attention to details. It develops routines that institutionalized the best practice at each production step and attaches specific quantifiable and assessable goals to them, and it uses real-time information to monitor the performance of both the individual components and the system as a whole. It diagnoses weak links and optimizes the linkages between processes. From the TIS lens, delicacy management is a framework that guides the managers to discover tacit knowledge embedded in their business operation that can be scaled up to improve the productivity of their human and financial capital. In so doing, it fulfills the ***knowledge development and diffusion*** function of TIS.

Delicacy management approach is appealing to Chinese PV manufactures because it is predicated on key principles like division of labor, quality control, and lean production, all of which contribute to the low-cost bottom line of Chinese PV manufacturers and their increasing desire to increase product quality. As a result, delicacy management is followed by a good number of tier 1 Chinese PV manufacturing companies. Among companies studied by this work, two tier 1 Chinese PV producers, (Trina Solar and Jinko Solar) two large second tier solar panel producers in Wuxi (Gaojia and Hareon Solar)[33] and one large supplier (GCL Poly[34]) all specifically mentioned delicacy management as a key element of their competitiveness, although this list does not mean to be all inclusive. Exhibit 1 in Appendix C uses a case study of GCL Poly to illustrate how delicacy management is implemented in Chinese factory in both a top-down and a bottom up manner in order to improve production efficiency and quality. Even with companies that did not specifically touted delicacy management, factory tours and interviews with their executives show that principles and practices resemble delicacy management are widely used. There is a strong taste among all Chinese PV producers and their major suppliers for some type of systematic and scientific management approach that reduces labor and material input, cuts waste in time and materials, and controls product quality.

In fact, the specific brand of the management style is not the quintessential part; Chinese firms’ pursuit for a scientific method to approach their growing industrial enterprise is at the heart of the story. In a way, delicacy management is an easy concept for Chinese companies to get on board with because it provides a philosophy and a methodology to deliver the outcomes Chinese manufacturing firms need, i.e. production

[33] Interviewee # 65, #71, #88, #91
[34] Tour ID #3; Interviewee #62, #63

cost reduction and product quality improvement. But the brand itself is a means instead of the goal. At the end of the day, Chinese PV manufacturing companies desire a systematic scientific management approach. Realizing that their traditional experience-based management approach was limiting, Chinese companies decided to pursue modern management methods that can transcend their business to a model that is better suited for global competition in the 21st century. Having a scientific management system is the standard practice of modern western companies (think about the World's Fortune 500 companies). By adopting delicacy management, or any other modern management approach for that matter, Chinese PV companies are conforming to existing rules to improve their ***legitimacy*** as leaders of the industry.

Conveniently, delicacy management matches well with the manufacturing culture and resources in China: it requires skilled worker; it drills down to specific details of a manufacturing process; it leverages process innovation for improvement and optimization; it requires an adoption of modern technologies; and it delivers cost reduction and quality improvement. To certain extent, delicacy management combines lots of the traditional advantages that Chinese firms have and the new values they want to pursue and packages them in a scientific way. It provides a scripture to upgrade business operation and unleash the previously untapped cost reduction and quality improvement potentials. The experience has so far been positive among Chinese companies as many of them attributing their global competitiveness partly to the adoption of delicacy management and other similar approaches[35].

Driving mechanism 4.4: The adoption of scientific management approaches improves companies' business and production performance and lends them legitimacy among their peers.

[35] Interviewee #58, #65, #71, #88, #91

4.3.3. Cultural Factors

4.3.3.1. Work Ethic

Work ethic in China is unique. Employees are wiling to put in extra hours at work so much so to an extent that it becomes a norm at some institutes. During a visit to a university research center on a Friday late afternoon, quite to the author's surprise, all graduate students and researchers were still at work at 6:30pm. Some of them were leaving for dinner but said they would come back after dinner. The same center also frequently meets on weekends to discuss research progress. Working long extra hours on a "voluntary basis" is common among office-based jobs. Examples of highly devoted employees are often praised for their work ethic and touted as role models for other employees to follow. It creates a hardworking culture (or a epidemic, depending on one's point of view).

For labor-intensive sectors like manufacturing, due to past high-profile labor rights dispute cases (Bilton, 2014; Clifford & Greenhouse, 2013), they are under heavy public scrutiny for labor exploitations. In terms of work hour regulation in China, the upper limit of work hours is set to be no more than 167 hours per mouth, equivalent to 21 8-hour working days per month.

All Chinese Tier 1 solar PV manufacturers run their production lines around the clock. Factories that operate at maximum or close to maximum capacity run on a 24/7 basis. They divide their workers into either four 8-hour shifts[36] or three 12-hour shifts. In so doing, companies are able to run their production capacity 24 hours a day 7 days a week while still comply with the law. These workdays may seem long from a western perspective, but it is common in the Chinese manufacturing sector. Workers are used to

[36] Three of the four shifts keep the production line up and running for three consecutive 8-hour segments while the fourth shift takes a day off.

such schedule and do not think twice with the night shifts and weekend shifts as long as they get their scheduled shift-off.

Workers are not the only group that is used to work in the evening and on weekends. As mentioned earlier, researchers, university professors are working bees too. But the list does not stop there. During the multiple research trips to China, the author had many meetings on weekends with people from all sectors, including universities, companies and government. A large number of these weekend meetings were conducted at interviewees' office where they stepped out from their weekend work schedule for a talk and then went back to work again after the interview[37].

There is no cheaper way to mobilize human resource than building a business culture that treats hardworking as a default. When working extra hours becomes a social norm or is even expected, the cost of extracting extra productivity from labor is close to zero (***resource mobilization***). However, the elephant in the room in this situation is issues related to labor rights. But the power of social norms is that they coerce certain behavior patterns and make it culturally acceptable. Section 4.3.5.4 on loose labor and environmental regulation will explore the negative side of such labor practice in more depth.

Driving mechanism 4.5: Hardworking culture in China mobilizes human resources at a very low cost and extracts productivity from them.

4.3.3.2. Pragmatic Mindset

Economic and social culture in China since the implementation of economic reform in the late 1970s has been inherently pragmatic in a sense that the country engages an experimental approach to economic development. Pragmatism as a school of philosophy centers on the role of experiment and experience in shaping ethic, value, belief, and knowledge (James, 1995). It advocates that those concepts could be best

[37] Interviewee #52, #60, #61, #64, #70, #81, #82, #93.

viewed through their practical use; and in order to get a flavor of their practical use, one needs to go out and do things, to practice, to conduct experiments, and use those experiences to inform his or her worldview and belief system (James, 1995; Morgan, 2007; Rescher, 1977). Pragmatism rejects ideology, theory, and even truth for their own intrinsic sake. Rather, it suggests that any of the above concepts would only be meaningful if it has a useful practical aspect. It resonates with Confucianism, which in part is a pedagogy that advocates for learning for the sake of serving the society.

Modern Chinese history, especially since the economic reform in the late 1970s, started to see pragmatism's influence on policymaking. The economic reform broke the ties with planned economy and adopted principles of market economy. It started in one pilot program and eventually rolled out to the whole nation, against strong ideological oppositions within the communist party. This action was inherently pragmatic because it proposed to let the results decide the legitimacy of the action, rather than leaving it to ideological criteria. This experiment-oriented policy approach can also be seen in China's design of its greenhouse gas regulations. China created 5 pilot cities and 2 pilot provinces since 2011 to test different carbon emission trading schemes. The cap-and-trade systems implemented by different cities and provinces vary from how they treat price floor, price ceiling, credit banking and borrowing, industry coverage, etc. The idea is to explore different policy design and understand their merits and drawbacks. Information collected at the municipal and provincial level directly informed the final design of the national cap-and-trade system, which was announced in September 2015. Exhibit 2 in Appendix C gives a short history of Pragmatism in China.

Driving mechanism 4.6: Pragmatism opened the doors for policy-related entrepreneurial experimentations in China, which changed the course of China's economy.

The point of referencing the pragmatic mindset is not to investigate the philosophical underpinning of contemporary Chinese economic culture, but to use it as a lens through which we can interpret the observations made about the solar PV industry and explain how they affect the competitiveness of the industry.

The pragmatic mindset is manifested at two levels in the solar PV industry in China. At the strategic level, the pragmatic mindset ***influences the direction of search***. Almost all players in the industry are committed to the notion that one does not innovate just for the sake of innovation. Rather, there should be social and commercial missions guiding all the endeavors (The innovation chapter detailed this mindset). At the process level, the pragmatic mindset leads to ***knowledge development and diffusion*** as the Chinese accomplish the social and commercial missions largely by conducting experiments. The remaining part of this section will elaborate on both points.

The social mission shared by many Chinese scientists and engineers is to make China self-sufficient in designing and producing all three generations of solar cells, instead of relying on foreign technologies and imported tooling and materials. The commercial mission is to capitalize on the technologies designed in labs by producing and selling them at a reasonably low cost. For a very long time, the goal of innovation in China had placed less emphasis on producing new or the best solar technologies (defined in cell efficiency terms), but on finding the right balance between technical advancement and commercializability. Players in the solar PV industry, from R&D, to material and tooling suppliers and eventually to cell and module manufacturers, all buy in to these pragmatic missions. They work in concert to develop and produce solar PV products that have reasonable efficiencies and can be mass-produced at a low price.

Empirical evidence from the past 15 years of solar deployment experience shows that the system cost is the number one determinant of market adoption. Even though economic theory suggests that products can differentiate from each other based on many other attributes such as quality, brand, etc. (Berry, 1994; P. Krugman, 1980), but none of them has been able to outweigh the significance of cost in determining PV technology adoption. (It is only since 2010 that market studies started to find a rising demand among customers for quality and efficiency.) Given the situation, Chinese's pragmatic mindset played a big role in determining which direction Chinese companies would go. Guided by the practical and yet basic concern for survival, the Chinese PV industry interprets this market phenomenon as to place issues such as highest solar cell efficiency as secondary concerns and focus on making lower cost products that can sell. Under such thinking, firms' strategy became finding the sweet spot on the "efficiency-cost spectrum" that delivers decent products but with a low enough price. In other word, the pragmatic mindset ***influenced firms' direction of search***: instead of pursuing high efficiency (high road firm strategy), Chinese companies decided to compete for low cost (low road). History later shows that Chinese solar panels successfully tackled the biggest barrier in early-stage solar PV adoption – high hardware cost – and gained a huge global market share (***market creation***).

Driving mechanism 4.7: The pragmatic mindset influenced the search for a business strategy and led Chinese companies to pursue a low-cost manufacturing strategy, which contributed to their dominance of the cost-sensitive mainstream market.

One example given by Advanced Solar Power (ASP), a rising Chinese CdTe solar cell producer, highlights this point. When comparing itself to the world's largest CdTe producer, the U.S. based First Solar, the chairman of the Chinese company pointed out that the entire production process at First Solar is conducted in clean rooms whereas only a number of steps are done in clean room in his Chinese factory. The rationale behind this so-called "selective sophistication" approach is that as sophisticated as it sounds, the marginal efficiency gain from producing solar cell in a 100% clean room environment is small yet the cost increment is relatively big. First Solar's average cell efficiency is two-percentage points higher than that of ASP, but the average cost is about 25% higher[38]. In the practical mindset of ASP, they would rather scarify the efficiency by a little bit in

[38] Interviewee # 72

order to keep the cost low. The selective sophistication approach gives ASP a boost in the efficiency-cost ratio, which they think is a "bigger bang for the buck". A similar example has to do with the decision made by many tier 1 Chinese companies to mass-produce Passive Emissive Rear Contact cell, a.k.a. the PERC cell (detailed in the innovation chapter). PERC on average has a higher efficiency than conventional silicon-based solar cells, but its efficiency is lower than truly high-efficient solar cell such as IBC or HIT. But the costs to produce IBC and HIT are higher because they require completely different manufacturing processes from conventional silicon solar cell whereas PERC only requires a moderate modification of existing silicon cell production line. Therefore, PERC has a lower cost than IBC and HIT. Once again, because of the better efficiency-cost ratio, most Chinese companies, with the exception of Trina, opted for making PERC as their high-end product. High cell efficiency is not the top priority of most Chinese PV manufacturers. Although they all intend to move up the value chain by providing higher efficient product, but the pragmatic attitude compels them to walk a fine line between efficiency and cost.

On the process level, Chinese are good at doing experiments. The CTO of Trina, Pierre Verlinden, said it this way

"Chinese are fierce experimenters."

According to him, the R&D personnel working for him do experiment at a speed that he has never seen. A Belgium native, Verlinden is a Stanford-trained world-renowned solar PV scientist. He was the technology-brain of Sun Power, the largest American silicon solar cell producer, in its early years. His experience spreads throughout Europe, the United States and Australia. Yet he said that his R&D team at Trina conducts experiments at a speed that cannot be matched by western researchers. This is partly because they are hardworking people, and partly because they believe in the value of experiments. It may sound unflattering, but the Chinese do experiments without much planning. They play it by ear; they do not wait until every detail of the research is sketch out to conduct experiments. Instead, they do them in an exploratory and experimental way. “Cross the river by feeling the stones” is the Chinese idiom that describes such approach.

Similar sentiment was expressed by the chairman of ASP, who himself had been a scientist at the U.S. National Renewable Energy Laboratory for 20 years before returned to his native land to become an entrepreneur. Instead of being an observer of the experimental spirit demonstrated by the Chinese PV researchers, he is one practitioner of it. He insisted that all manufacturing equipment used in his factory need to be self-designed and domestically manufactured because he wants to be able to conduct experiments with them quickly and easily[39]. More examples of conducting experiments with domestically produced equipment will be introduced in the supply chain chapter of this dissertation.

Just like they do not innovate for the sake of innovation, the Chinese do not conduct experiments for the sake of the deed only. Experimentation is their methodology for discovery. It is low-key, and that is a feature rather than a bug. Low-key means that the barrier for participation is also low, which allows a greater number of people can participate rather than just the elite few (***resource mobilization***). It enables process innovations that are carried out by workers at the most grass root level of a production process, in addition to other more knowledge-demanding types of innovation. In fact, China is known for process innovation, which, despite its low-key nature, is proven to be a cost effective way to improve product quality and also lower the cost. This brings the logic to a full circle because pragmatic mindset at the strategic level in the solar PV industry also seeks to strike a balance between quality and cost. The goals at both the strategic and process level are compatible and congruent. As a result, they enable and legitimize each other.

[39] Interviewee #72

Driving mechanism 4.8: Pragmatism encourages experiment-based *knowledge development and diffusion* with a broad participant base.

Admittedly, the pragmatic approach has its limitations. One has to be very careful to not slip into interpreting pragmatic as "whatever works". Yet, some players in the Chinese PV industries are certainly guilty of such interpretation. When pursuing lower production cost, some manufacturers cut corners by using cheaper and inferior materials. In keeping up the commercialization mission, researchers sometimes trade in-depth scientific investigations for short-term research that yield results faster. While Chinese R&D personnel are praised for their fast experiment speed, their experiments are often experience-based and lack of sound theoretical guidance. Last but not least, the pursuit of economic efficiency makes manufacturers and researchers become better and better at developing routines to make cookie-cutter products at the cost of diversity, novelty, and creativity. Issues with product quality, lack of innovation capacity, and cheap but non-differentiable solar panel products all hurt the ***legitimacy*** of the industry.

Blocking mechanism 4.1: Untruthful interpretation of pragmatism led to short-sighted research and business practices that harmed the reputation of the Chinese solar PV industry.

The pragmatic mindset has allowed the PV industry in China to be flexible, cost-sensitive, and innovative at the process level, which are all important abilities to have in order to compete in the marketplace. But pragmatism as practiced in China does not offer a long-term view for companies that look to transcend their business beyond competition at the price point.

4.3.3.3. Desire to Reduce Cost

Players in the Chinese Solar PV manufacturing sector have strong indigenous desire to continuously reduce cost. Their unabashed pursuit of product cost reduction through various means are outstanding. Coming from the country's long low-cost manufacturing culture, Chinese solar PV manufacturing sector inherited the cost imperative from a long list of industries that came before it. They built China's bone fides as the world's factory and the supplier of affordable products. Chinese take pride in their ability to produce goods cheaply. Today, Chinese PV manufacturers are pursuing low-cost manufacturing harder than ever because China's cost advantage over other countries is shrinking these days due to factors like rising labor cost, currency appreciation, and trade tariffs which drive Chinese manufacturers to look into other factors like innovation for future growth. Just like the vice president of a GCL Poly said in an interview

"Cost reduction is baked in the manufacturing culture in China. This unabashed chase for lower cost throughout the entire supply chain is hardly seen anywhere else in the world."[40]

Indeed, the motivation to reduce cost permeates the entire Chinese solar PV supply chain and is wholehearted embraced by all the players. Solar cell and module producers naturally demand lower cost because they directly face market competition. Their demand translates inwardly into their own organizations and outwardly to their technology, tooling and material suppliers and ***influenced*** their ***direction of search***.

Within the production entities, managers build a company culture that places high priority on cost reduction. Taking a tour at any Tier 1 Chinese solar PV factory, visitors will see some version of "strive to achieve cost reduction" on a banner hanging at the most noticeable place in the workshop. Engineers, technicians and production line workers are all encouraged to contribute to the cost reduction quest through either low-key process improvement or highbrow innovation. Often time, companies set up incentive programs to invite new ideas from their employees, and ideas that are proven to improve manufacturing performance improvement and reduce cost will be financially rewarded (Exhibit 1 in Appendix C).

[40] Interviewee #57.

The desire to continuously lower the production cost does not only exist inside PV manufacturers; technology developers, tooling and material suppliers also share the drive to reduce cost. As noted in the innovation chapter, Chinese researchers in the solar cell realm are generally practical-minded in a sense that they care about the commercializability of their technologies as much as they care about technical merits. After talking with a large number of solar scientists in China, especially those who work on the first-general solar cell, it is noticed that very few of them agrees that they will trade low-cost and manufacturability for higher solar cell efficiency. The fact that almost all the leading solar cell scientists in China are collaborating with Chinese manufacturers on R&D projects suggests that their direction of search is influenced by companies, making them sensitive to cost and production feasibility. It, in turn, creates a concerted effort between technology developer and manufacturer to reduce cost.

Finally, the desire to reduce cost receives a large buy-in from the supply chain. Indigenous to China's manufacturing culture, suppliers are sensitive to cost too. In order to compete in the market, tooling and material suppliers need to prove their cost competitiveness, too. This is simply a market dynamic. In addition, there is an organized effort lead by big PV producers to engineer supply chain-wise cost reductions. In other word, large PV producers ***mobilize resources*** contained in the supply chain to achieve deeper cost reduction. Large leading Chinese PV manufacturers hold annual suppliers conventions. Among the many purposes of such conventions, communicate the PV manufacturer's goals of near-term and their long-term cost reduction with its suppliers is one of them.

According to Bloomberg New Energy Finance's analysis of Tier 1 Chinese companies' production cost, 65% of solar cell production cost is material related, the portion is higher for solar module production – 78%. Manufacturing equipment cost accounts for another 20% and 5% for cell and module production, respectively, using the predominant depreciation rule used by Chinese companies (BNEF, 2014b). As a result, material and tooling related costs for cell and module production take up 85% and 83% of the total production cost. It means that much of the final cost reduction has to come from the supply chain. The communication about cost between the buyer (Chinese PV manufactures) and the suppliers is one way to directly tap into the cost reduction potential in the supply chain. Buyers squeeze their suppliers, push them to deliver better product at a lower price. The large production capacity of the top tier Chinese companies, usually at the level of 2-3GW, means that they have a big bargaining power over their suppliers. The power dynamic puts the PV manufacturers in the position to initiate the supply chain-wise cost reduction effort, to motivate their suppliers, some times even pit them against each other, to achieve the final cost goal. On the suppliers' side, their desire to stay competitive and retain the customers would motivate them to come up with ways to reach the cost reduction goals, usually through ways such as increase production productivity, using alternative cheaper materials, fundamentally redesign a higher performance, lower cost product, or even squeeze their own suppliers etc. In a way, the suppliers and PV manufacturers use some of the same mechanisms to reduce cost because they are all manufacturing companies at their core, despite of different scale.

Generally speaking, the desire to reduce cost is strong in the PV manufacturing industry in China and all players at each step of the supply chain share this drive[41]. The long tradition of producing affordable goods gives Chinese PV manufacturers a mindset that motivates them to keep pursuing further cost reduction. There is no observable self-consciousness among Chinese players in the industry. Instead, they are proud of their cost-oriented approach and credit large part of their success to it. They credit their large market share to their cost advantage (***market creation***).

Driving mechanism 4.9: Chinese PV manufacturers' desire for cost reduction *mobilizes* a concerted effort to do so throughout the entire supply chain and *influenced* their suppliers' *direction of search*.

[41] Interviews #47, #52, #58, #59, #65, #71, #73, #89, #96, #97, #98, #104

In the meantime, the Chinese are also surprisingly frank with the downside of their approach, i.e. lower cell/module efficiency, lower product quality. The heavy emphasis on low cost has taken away energy that could have been spent on research and development, quality control etc. Similar to the drawback related to the pragmatic mindset, problems stemmed from these areas hurt the reputation and the legitimacy of the industry. Evidence presented earlier in this chapter and in the innovation chapter show that measurers have been taken to address the issues. However, the pursuit for low-cost production is not going to change, as expressed by the deputy director of the 48th Institute *" It may sound paradoxical, but companies need to producer better products at lower costs in order to stay competitive in the market."* [42]

Blocking mechanism 4.2: Single-minded pursuit for low-cost led to problems with product quality and lack of real innovation which hurt the reputation of the industry.

4.3.4. Resource Factors

4.3.4.1. Skilled Labor with Low But Rapidly Rising Cost

Historically, low labor cost had given China a huge cost advantage in manufacturing; it was the primary reason why multinational corporations moved to China in the 1980s and 1990s. Bureau of Labor Statistics at the U.S. Department of Labor reports that the average hourly compensation for manufacturing employees in China was only $0.74 in 2004 (U.S. Bureau of Labor Statistics, 2015b), compared to $29.31 in the U.S. in the same year(U.S. Bureau of Labor Statistics, 2015a). Both numbers include basic wage and social benefits and insurance. The large population base in China created an abundant supply of labor, which is the main reason for the shockingly low wage in China. Even compared to its Asian peers, China's wage in early 2000 was still an outlier.

[42] Interviews #104

Taiwan's average hourly compensation wage in 2002 was $7.28. Philippine was the closest to China, but it paid a higher amount at $1.1.

The low wage had allowed Chinese manufacturers a huge cost competitiveness in industries like textile, apparel, and toy industry where labor intensity is high. Solar PV manufacturing has a mid-level labor intensity. It certainly benefited from the nation-wide low labor cost, although to a less extent relative to other labor-intensive industry. Furthermore, the increasing level of automation has decreased the labor requirement by PV producers by a significant amount. For a 30-35 MW solar cell production line, it used to take up to 120 people to operate. Today, a well-automated cell production line only requires about 30 people to keep it running. As a result, labor cost only accounts for about 10% of the final product cost[43]. As a result, even if labor cost remains low, it only affects a small portion of the production cost.

However, all signs suggest that labor cost is rising in China. Just like China's economy grew at double digits every year between 2004 and 2013, labor cost has been growing rapidly too. By 2009, hourly compensation in the manufacturing sector grew to $1.74, a 235% jump from its 2004 level. Latest data show that the average annual wage tripled between 2004 and 2014 (China Labour Bulletin, 2015). The rising standard of living in China, policies that require and enforce minimum wages, and the lower supply of labor all contributed to the rising labor cost. Interviews with executives at large Chinese PV manufacturers revealed that China is no longer the lowest cost country mostly due to the rising labor cost[44]. Companies are looking at Southeast Asian countries like Malaysia, Thailand, and Vietnam as potential outsourcing destination for their lower labor cost.

Interestingly, even if the labor cost is lower in certain Southeast Asian countries, companies with factories located in those countries still report a higher production cost.

[43] Interviewee #8, #51, #54, #79, #96, #100
[44] Interviewee #57, #63, #67, #96

Insights from company executives[45] suggest that weak supply chain in countries other than China drives up the cost. In addition, productivity in those countries also suffers from unskilled labor.

In fact, China's labor related advantage is not limited to just low cost. Its large pool of well-trained skill labor also makes a difference. Scholars have long stressed the importance of skilled and educated labor to firms' competitiveness (Susan Christopherson & Clark, 2007). In the example of the Chinese solar PV industry, production line workers at tier 1 Chinese PV producers usually are high school graduates; a large portion of them graduate from vocational schools where they were trained with manufacturing skills. Engineers and technicians often have college degrees and understand basic mechanical designs of the machines. Besides education level, experience also matters when it comes to evaluating the quality labor force. As described above, large Chinese PV manufacturers concentrated in manufacturing hub regions with long industrial tradition, where the labor pool is not only large, but also skilled, experienced, and multi-talented. Their knowledge diffuses from one manufacturing sector to another ***(knowledge development and diffusion)***. The workers recruited by PV companies are often not green hands. Instead, they are likely to be veteran workers with years of experience in a related industry. They had already received training and accumulated experience with operating machinery and performing tasks on production line by the time they came on board. They are a key part in building China's manufacturing advantage.

4.3.4.2. Ready Infrastructure

Infrastructure in China has come a long way since the beginning of its open door policy in the late 1970s. China today has an impressive portfolio of infrastructure, including the world's largest high-speed railway system and expressway system, a

[45] Interviewee #54, #57, #58, #67,

rapidly growing aviation network, and an expansive electric grid featured high voltage and ultra-high voltage transmission line.

China's has the world's largest railway system and the world's largest high-speed railway system. The latter spread over 11,250 miles (18,000 km) by the end of November 2015. A similar length is currently under construction or in planning (Securties Daily, 2015). High-speed trains travel at a minimum 124 miles/hour (200km/h). An 824 miles (1318km) high-speed train ride from Beijing to Shanghai, China's largest two cities, takes less than 5 hours. The system transported an average of 2.49 million riders per day in 2014, and has 3.16 billion riders since its initial operation in 2007 (Securties Daily, 2015). Some of the passenger high-speed railways also transport freight. In addition, there is another 2,760 miles (4,000 km) of high-speed rail just for freight. This network of high-speed trains connects all but two Chinese mainland provincial-level jurisdictions.

Even more expansive is China's expressway system. It is estimated that the Chinese expressway system surpassed the U.S. Interstate Highway System in 2011 to become the world's largest highway network by length. As of 2014, the total length stood at 69,560 miles (111,950 km) (Ministry of Transportation of the People's Republic of China, 2014).

China has also been building a large number of airports. There were 182 commercial airports in China at the end of 2012, the 12th FYP called for adding another 82 airports between 2011 and 2015 (China Daily, 2012). The medium term planning foresees a future with 244 airports by 2020.

Both theory and empirical evidence suggests that transportation infrastructure is a necessary factor for economic development. Public investment in infrastructure is more efficient than private investment and it boosts the private sector productivity both within and beyond the region where the investment was directly made (Cohen and Paul 2004). The logic is simple and easy: modern production networks, may they be regional or global, require an interconnected web through which goods and services can be produced, distributed, and consumed (Coe, Dicken, and Hess 2008; Coe et al. 2004; Lazzarini, Chaddad, and Cook 2001). Manufacturing industries require goods to be physically passed around. A well-developed transportation infrastructure allows producers and suppliers to connect with each other at a low transaction cost. The convenience of material transportation can also expand the manufacturers' sourcing scope (where they buy inputs from) and their reach to end markets.

Even for the Chinese solar PV manufacturing industry where the supply chain is more clustered and compact compare to many other counties, good transportation infrastructure can still allow them to manage their inventor in a timely and dynamic fashion. As a result, PV manufacturers do not have to carry heavy inventory; instead, with easy and low cost transportation, they can order supplies with short lead-time. Smaller on-site inventory stock improves PV manufacturers' cash flow, which means they can spend less of their short-term cash spending on stocking input materials. This improves companies' financial flow and allows them to be agile and lean in their production. Most emerging Southeast Asian countries suffer from their less developed transportation infrastructure. Even though they have a labor cost advantage, it is offset by the logistic-related limitation.

Besides transportation infrastructure, China also has a massive electric power sector and an increasingly modern electric grid. The electric power system in China is the world's largest; it has 1505 GW of generating capacity which generated 5583TWh of electricity in 2014 (CIA, 2015). Providing electricity access has long been seen as a priority by the communist government. In Mao's era, electricity provision was seen as a quasi public good that should be provided by government. Since the economic reform in the late 1970s, electricity access was seen not only as a social mission, but also a necessity for economic development. Regardless of the rationale, multiple government led campaigns expanded electricity grid to rural counties and townships. As a result, despite its large population, China has a high level of electricity access. World Bank reports that electricity access in China was 94.3% in 1990. The number rose to 99.7% in 2010. By 2011, 100% of Chines population had electricity access (World Bank, 2015).

The relentless effort to provide electricity service builds a foundation for China's economic development. Today, even as companies look to Southeast Asian countries for the next place to manufacture goods, they all acknowledge that the lack of reliable access to electricity in those countries is a big concern of them (Patel, 2014). 1 out of 10 people without electricity access lives in Southeast Asia. Even in regions with electricity access, the quality of the electricity and reliability of the grid is a big concern. In an interview with a tier 1 Chinese company that has a Southeast Asian factory, its vice president told the story about their Southeast Asian factory having to downsize their production because it demands high electric voltage and stable frequency that the grid of their Southeast Asia host country was unable to provide[46].

Besides access to grid and grid quality, the grid connection for new manufacturing plants is relatively easy and swift in manufacturing regions in China. Land in China is public-owned and therefore, when it comes to extend transmission infrastructure to new areas, there is almost no property right issue to be battled out, unlike in countries such as the U.S. where private property owners have veto power in approving new transmission projects and often engage in long bargaining and negotiations process with transmission authorities.

In summary, the solar PV manufacturers in China do have an electricity-related advantage, but it is not the low cost, as conventional wisdom usually portrays. The conventional wisdom may be true for the residential sector, which is heavily subsidized by the government for social reason, but for the industrial and commercial sector, the average electricity rate is higher in China than, for example, in the U.S. Table 4.6 compares a list of key production factors between leading Chinese and American solar

[46] Interviewee # 57.

panel production firms. On average, Chinese Tier 1 companies pay higher electricity rate, and the difference is statistically significant.

Table 4.6 A List of Key Production Factors,
A Comparison Between Tier 1 Chinese and American Firms

	U.S. Average	China Average	T-Test^
Production Cost ($/W)	3.14	2.79	No
Electricity Rate ($/kWh)	0.08	0.09	**
Average Interest Rate (%)	2.98	3.88	**
Effective Tax Rate (%)	12.85	8.02	No
Module Capacity (MW)	613	1090	**
Module Production (MW)	170	218	**
R&D Spending (%)	3.16	1.52	**

^Note:
** Indicates the difference is statistically significant at 0.05 level
No indicates the difference is not statistically significant
Data source: Bloomberg Solar Industry Database

The real electricity-related advantage in China is the electric infrastructure that provides not only access to the quintessential production input, but also with reliable grid and good electricity quality. These features ensure the productivity of the PV manufacturing plants. Finally, the fact that grid connection is made easy and fast also makes continuous manufacturing capacity expansion possible.

Both low-cost skilled labor and ready infrastructure are not advantages unique to the PV industry in China. They are shared across all the sectors. The most significant way they contribute to the development of the solar PV industry is that they enable the ***development of positive externalities*** that allow other parts of the system to function at a more efficient and productive way.

4.3.4.3. Easy Access to Capital (Historically)

Conventional wisdom often dismisses the cost and difficulties to obtain capital in China, thinking that loans and investment are at debtor's disposal. However, the fact is that capital is not inexpensive. Rather, the interest rate charged in China is even higher than it is in the U.S., as shown in Table 4.6. The bond buying program and the quantitative easing approach used by the United Sates Federal Reserve Bank have kept the interest rate in the U.S. extremely low since the 2008 global financial crisis. It dramatically lowers the interest rate for American firms to take on loans for PV manufacturing firms. However, the People's Bank of China (PBOC), a.k.a. China's central bank, has kept the benchmark lending rate at no lower than 5.1% in the post financial crisis era, which results in higher costs to access capital in China. Table 4.7 shows the history of benchmark lending rate adjustment in China since the 2008 global financial crisis. The rate was as high as 7.41% right before the crisis. It dipped to 5.31% by October 2010 in an attempt to stimulate the economy by the PBOC. It rose back to 6.31% by July 2012 but fell again since then as the Chinese economy entered a medium growth rate period. Regardless of the downward adjustments, the cost to borrow money in China today remains high. Just for comparison, during the same time period, interest rate in the U.S. was kept at 0%.

Table 4.7 Benchmark Lending Rate Adjustments in China Since 2008 Financial Crisis

Date of Adjustment	Before Adjustment	After Adjustment
May 2015	5.35%	5.10%
March 2015	5.60%	5.35%
November 2014	6.00%	5.60%
July 2012	6.31%	6.00%
June 2012	6.56%	6.31%
July 2011	6.31%	6.56%
April 2011	6.06%	6.31%
February 2011	5.81%	6.06%
December 2010	5.56%	5.81%
October 2010	5.31%	5.56%
December 2008	5.58%	5.31%
November 2008	6.66%	5.58%
October 2008	7.20%	6.66%
September 2008	7.41%	7.20%

It is a myth that money is cheap to obtain in China, but Chinese companies do benefit from uninterrupted capital flow while the capital markets in Europe and the U.S. were largely frozen in the wake of the 2008 global financial crisis.

Bayaliyev et. al. found that the amount of loans provided to Chinese PV manufactures in 2010 and the first half of 2011 could be as high as $40 billion. (Bayaliyev, Kalloz, & Robinson, 2011) Former Secretary of Energy Steven Chu had said in a Congress testimony that China Development Bank alone provided $34 billion to PV manufacturers within eighteen months in 2010 and 2011. His testimony highlighted a key financial player in the development of the Chinese PV industry, China Development Bank (CDB). Owned solely by Chinese central government, CDB is a “policy bank”. Its primary role is to facilitate the nation’s economic development according to government policies. As the economic development arm of Chinese government, CDB has financed thousands of projects involving infrastructure, energy, strategic industry, and etc. The PV manufacturing industry falls under the categorical of emerging industries, and had received large amount of loans form CDB.

Compared to venture capitals and investment banks in the west, which make their decision based on market risk and returns, CDB makes its lending decisions only partially based on market-oriented criteria. To a large extent, CDB’s lending decisions were heavily influenced by the economic plans and policies the central government issues. This reflects the unique reality of Chinese economy. While the economy is going through a transition from a central-planned economy to a market-based economy, both types of economy have their influences on CDB’s business model. On the one hand, it functions like a private investment bank that lends money and expects returns on its capital. On the other hand, it carries out national economic development plans by shouldering the investment risks with the private players and being the first one to lend to emerging industries.

The biggest contribution of players like CDB is that they enable the financial liquidity, or in TIS framework language, they facilitate financial ***resource mobilization***. Chinese PV manufacturers were able to assess capital relatively easily, especially during the time where creditors in the West were reluctant to lend debt seekers, including European and American PV manufacturers, during the global financial crisis. The ability to access capital allowed Chinese manufacturers to expand their production capacity and to take advantage of the renewable-energy-friendly stimulus package in the world's major economies (***market creation***). For example, evidence collected by the Stanford China Solar Project show that CDB offered substantial corporate debt between 2009 and 2011. In its peak year, CDB issued a $30.41 billion credit facilities to five leading Chinese PV manufacturers, JA Solar, LDK, Suntech, Trina, Yingli, in 2010. Between 2005 and 2013, CDB dominated in the provision of corporate debt, extending $31.35 billion in credit facilities to Chinese PV manufacturers, which accounts for 93% of the total (Steyer-Taylor Center for Energy Policy and Finance, 2016). But again, the cost of CDB's capital is not cheap. Available company financial documents compiled by Bloomberg Industry SOLAR (Bloomberg Finance L.P., 2014a) and interview with a CDB official[47] all confirm that CDB loans were charged market interest rates, which includes a base rate around 6% (slightly higher than the then benchmark lending rate set by PBOC) and a market prime rate, which is decided on a case by case basis according to companies' bankability, plus fees. It can be argued that the advantage of having policy banks like CDB is that Chinese PV manufacturers did not have the same difficulties as their Western competitors do in terms of proving their bankability in order to access debt. However, for the money they borrow, they pay a good amount of interest rates.

In addition to CDB, other national commercial banks such as the Export-Import Bank of China and Bank of Communication, and local banks in Jiangsu, Hebei, and Zhejiang Province have also financed the PV manufacturing industry.

[47] Interviewee #60

Driving mechanism 4.10: Easy access to capital in China allowed Chinese PV industry to gain financial resources to sustain its growth at a time companies outside of China struggled with access to capital.

It is fair to say that historically, easy access to capital allowed then existing Chinese PV manufacturers to quickly expand their production capacity and fostered the creation of many new PV production companies. However, because the lending was driven by both market demand and national policies, arguably, acts like the CDB loans in 2010 had contributed to an environment where credits were too easy to get. Policy-driven lending made financial prudence, which is supposed to be the key criterion in a lending decision, take a backseat. It led to capital flow into building new factories that was based on self-reinforcing hypes rather than on prudent market analysis. This rapid expansion of capacity eventually resulted in the accumulation of large amount of excess capacity, an overflow of low-quality, low-efficiency solar PVs, and the trade dispute with E.U. and U.S.

Blocking mechanism 4.3: Easy access to capital in China scarified financial prudence and led to the building of financially unsound projects that sow the seeds for the later industry crisis.

Since 2012, policy banks and commercial banks have dialed back their lending to the PV manufacturing sector, partly due to problems with excess capacity and partly because of the free-market-oriented financial sector reform in China, Chinese PV producing companies no longer enjoyed the easy access to capital. Instead, they are now on their own to secure finances. Interviews with a number of CFOs of leading Chinese PV manufacturers[48] all suggest that as CDB's intervention drew down, so did the magnitude of corporate debt that the companies are able to get. It reflects the new reality in the PV manufacturing sector in China, which is access to the debt market is becoming more and more difficult because the profit margin of solar cell and PV manufacturing is

[48] Interviewee # 54, # 79, # 96, # 100

very thin due to the fast dropping solar panel price. Although companies compensate the lack of corporate debt availability with other financial sources such as the stock market and private equity, the truth of the matter is that even though Chinese companies historically had an advantage in access capital, the changes in market place and policy direction have largely removed the advantage.

4.3.5. Policy Factors

4.3.5.1. A National Vision and Industrialization Strategy

The Chinese solar PV manufacturing sector benefited from the national vision and an industrialization strategy for the industry. The vision and the strategy created ***legitimacy*** for the industry, ***mobilized resources***, and ***influenced the direction of search*** of industrialists, and invited ***entrepreneurial experimentations***. Scholars have theorized and empirically proved that national visions and strategies are important and beneficial to a nation's manufacturing industry (Bryson, Clark, & Vanchan, 2015; Clark & Clavel, 2012; Clark, 2012; Mitchell, 2010).

In 2000, the solar industry appeared for the first time in the nation's 10th Five Year Development Plan, the single most important economic development of the country. Although there could be multiple ways to approach the solar industry, i.e. to approach it as an alternative energy industry or as a technology innovation subject, the Chinese government treated it as a manufacturing industry with both domestic and international market potentials. From a strategic perspective, the 10th FYP set the tune of industrializing the manufacturing of renewable energy technologies, including solar PV. The fundamental principle promulgated by the plan was "industrial development through creating economies of scale". It emphasized the scaling up of solar cell and panel production and the development a robust PV supply chain to create agglomeration economies. It sets specific panel manufacturing and supply chain development goals by calling for a 15 MW annual solar cell manufacturing capacity and a fully-developed PV module supply chain by the end of 2005. These clear policy signals set a trajectory for everybody who wanted a piece of the solar PV pie to follow. In fact, they mobilized a diverse group of entrepreneurs and industrialists to take part in the industry (***resource mobilization***). Seeing the market opportunity created by the national vision oversea-trained Ph.D such as Suntech's former CEO Shi Zhengrong, local entrepreneur like Yingli's CEO, Miao Liansheng, and self-made industrialists like Trina's CEO Gao Jifan all entered the market with their respective specialties. Furthermore, their companies all followed the industrialization strategy, i.e. economies of scale, while building their PV manufacturing business. The national vision and industrialization strategy's significantly ***influenced*** their ***direction of search***, and arguably owed its early stage success to the vision and strategies laid out in the FYP.

Economies of scale production and supply chain development continued to be the emphasis in the 11th FYP (2006-2010), albeit innovation and solar deployment started to gain momentum during that period too. During this period, the solar PV manufacturing industry has achieved its ***legitimacy*** not only as an industry while it became a poster child of China's export-oriented economy. It did not only gained global market dominance, but more importantly did so with its own brands like Suntech, Trina, Yingli, etc.

In the 12th FYP (2011-2015), acknowledging the industry's reliance on import for key tooling and material inputs as well as the low value-added products it produce, the strategic focus of the industry planning shifted from creating economies of scale to integrating solar supply chain development with innovation, aiming to achieve higher level of supply chain self-sufficiency and produce higher-efficient solar panels. The new strategy once again ***influenced the direction of search***. As detailed in the innovation chapter, more financial and human resources were devoted to solar cell R&D. The next chapter will discuss how domestic players increased the level of manufacturing equipment self-sufficiency through R&D. The take home message is that the evolution of the industry did not happen purely organically. Rather, policy and strategizing played a big role in mobilizing innovation, manufacturing and financial resources to tackle the industrialization goals outlined in the FYP.

When the industry was hit by restrictive trade measures coming from Europe and the U.S., a suite of industrial standards were issued by the Chinese Ministry of Industry and Informational Technology (MOIIT) to set the minimum requirements to further strengthen the innovation and manufacturing capacity, and increase the product quality of domestic companies. The result of the industry standards was that large self-sustainable firms solidified their positions while small and financially vulnerable companies were either acquired by large firms or existed the market competition.

A body of literature argues that the biggest difference between China and western economies, represented by the U.S., in terms of how industries are run is that the former has a set of industrial policies while the latter shuns away from it (Dobbin, 1994; C Freeman, 1987a; Christopher Freeman, 1989; Prestowitz, 1988). This dissertation argues that both countries have industrial policies in one form or another. Corporate tax breaks, investment tax credits, and business development grants existed in the U.S. are in essence industrial policies. It is just that for political reasons the phrase industrial policy is avoided. The quintessential difference between industrial development in China and the U.S. does not lie in the use of industrial policy, but rather in whether one uses national vision and strategies to ***legitimize*** a technology by making a commitment to its development.

To support an industry is to make a technology choice for the future. The decision made by the Chinese government to promote renewable energy industries decided that renewable technologies would play a bigger role in the country's energy mix. The battle over solar in many U.S. states are not simply a disagreement about the merits of the technologies. In fact, opponents of solar are well aware of the technology's merits and its potential to erode fossil future energy's future market share. To fight against solar is the incumbent players' attempt to ensure they stay relevant in the future.

In absence of a national vision and industrialization strategy, technologies would have to fight it out. Neo-classic economics theory predicts that in an ideal free market, new technologies with real value will prove themselves eventually and replace the incumbents. However, it failed to acknowledge that industrial development is risky, unpredictable, longwinded, and requires a lot of serious efforts, rather than costless, spontaneous as neo-classic economics theorists assume (Bergek et al., 2008; Clark, 2013; Sanjaya Lall, 2004; Mitchell, 2010; R R Nelson & Winter, 2009; Rodrik, 2004). Plus, the ideal conditions descripted by theory never exist. Markets in real world are full of distortions that favor incumbent players. Therefore, an organic growth of a new industry will have to break a lot of barriers. Odds often stack against them.

The Chinese solar PV industry has benefited from the national vision and strategies that the central government laid out. The national vision created policy certainty; the economies of scale production and supply chain development strategies set the industry in a fast lane for development from the very beginning and enabled them to develop strength to seize the market opportunities in E.U. and the U.S. Later, the strategic shift from economies of scale to innovation along the entire value chain after 2013 meant to facilitate the industry restructuring in the aftermath of trade conflicts. The vision and strategies implemented at the national level create a concerted, rather than fragmented, effort to facilitate the development of the industry.

Driving mechanism 4.11: China's national vision and industrialization strategy for solar PV lent the initial legitimacy to the industry. The perceived legitimacy mobilized entrepreneurs and industrialists to enter the market. The expectations brought forward by the national vision and strategy also influenced the players' direction of search in order to realize the expectation.

4.3.5.2. Government Subsidies and Incentives

4.3.5.2.1. Facts and Anecdotes of Government Subsidies and Incentives

When it comes to unpacking the manufacturing advantages in China, government subsidies and incentives are controversial areas. Granted, government subsidies are one way to lower the cost of production besides other public benefits that they provide such as improving labor skills, infrastructure readiness and capital accessibility (Lall 2004). Subsidies for the industrial sector, along with trade policies, are frequently labeled as sub-categories of industrial policy. However, they are often seen by neoliberals as interventional, inefficient and protective (Noland & Pack, 2003; World Bank, 1993). Proponents of industrial policy have argued that from both empirical and theoretical perspective, there can be a healthy role for the government beyond what neo-classical economic theory is willing to prescribe. From a historical perspective, Wade, in his book Governing the Market (Wade, 2003) argued that,

"The remarkable thing about the core Washington Consensus package is the gulf between the confidence with which it is promulgated and the strength of supporting evidence, historical or contemporary. There is virtually no good evidence that the creation of efficient, rent-free markets coupled with efficient, corruption-free public sectors is even close to being a necessary or sufficient condition for a dynamic capitalist economy. Almost all now-developed countries went through stages of industrial assistant policy before the capabilities of their firms reach the point where a policy or (more or less) free trade was declared to be in the national interest."

There are many types of subsidies in use in China, among those the following five types are commonly used by MOIIT and National Development and Reform Committee (NDRC) to support the solar PV industry: investment subsidies/grants, tax incentives, inputs subsidies, preferential lending, and infrastructure and social welfare contributions (Bayaliyev et al., 2011; Deutch & Steinfeld, 2013b; Sun, 2013).

The following section provides a summary of solar PV-related government subsidies and incentives, and an analysis of how they affect the PV manufacturers in China. It needs to acknowledge that because of the trade conflicts with E.U. and U.S. over government subsidies, it is sensitive to discuss them with government officials and company executives in China. Collecting comprehensive data on them is even harder due to information restrictions. What is presented here is an incomplete list of solar PV related subsidy and incentive programs based on the two countervailing duty investigations conducted by the U.S. Department of Commerce (DOC) against Chinese PV manufacturing industry from 2012 to 2014 (U.S. Department of Commerce International Trade Administration, 2012b, 2014b) and anecdotal information collected from semi-structured interviews in China conducted by the author and her colleagues from the Stanford China Solar Project team. They meant to provide a peek into the nature and forms of the industrial policies in China. Table C.1 and Table C.2 in Appendix C provide information on findings from the US DOC investigation and anecdotal examples, respectively. Information collection and table compilation were conducted as part of the Stanford China Solar Project.

Investment subsidies/Grants

Similar to the Investment Tax Credits (ITC) in the U.S., investment subsidies mainly takes place in the deployment sector, but because large Chinese PV manufacturers all have a sizeable deployment division in operation, deployment subsidies such as the Golden Sun program, Thousand Roof program, and Feed-in Tariffs can also be leveraged by PV manufacturers to diversify their revenue flow. Next section will discuss the role of these solar PV deployment-oriented programs in detail.

There are also grants given to companies. These are cost-free capital hangouts from provincial and local governments to companies, often earmarked for particular purposes such as R&D, overseas expansion or marketing. Table C.1 in Appendix C includes more details.

Tax incentive

Tax incentives given to Chinese PV manufacturers usually take on three forms: refund of value added tax (VAT), refund of corporate income tax, or both. Under the Renewable Energy Law, qualified PV manufacturers can apply for exemptions of half of their VAT. Corporate income tax can also be fully exempted in the first three years of the plant operation, and then be halved for the next three years. Many local governments also offer incentive packages that exempt the VAT and corporate income tax by certain amount over a period of time (Grau et al., 2012). See Table C.1 in Appendix C for more details.

Input subsidies

In principle, NDRC allows preferential land contracts for industries that are promoted in the FYPs. Specific contract terms vary by projects. By some account, the rent for a manufacturing plant can be as low as $150 to $250 (¥900 to ¥1500) per thousand square meters[49]. On top of what is sanctioned by the central government, local governments often allow large manufacturing companies to rent or purchase land with a deeper discounted. Interview with City of Wuxi government shows that it provided favorable land lease terms to the Suntech[50]. The countervailing investigation conducted by the U.S. DOC confirmed the finding (U.S. Department of Commerce International Trade Administration, 2012b, 2014b), and listed City of Changzhou and City of Xinyu as providing subsidized land to Trina and LDK solar, the finding of which was also confirmed by interviews with local officials conducted by this study [51].

Besides subsidized land, there are also documented incidents of input subsidies on polysilicon and aluminum. See Table C.1 in Appendix C details.

Preferential lending

[49] Land subsidies http://baike.baidu.com/view/7114578.htm
[50] Interviewee #92
[51] Interviewee #81, #82, #91, #92

As discussed earlier, the capital advantage that Chinese PV companies had was not mainly in terms of low interests rate but the low hurdle to access capital at a time when other world major economies experienced a contraction in capital provision. U.S. DOC's investigation mostly supported this argument. None of the loans that companies received from CDB were called out in the investigation, affirming their legality. However, the other policy bank, the Export-Import Bank of China was found to provide low interest loans to Chinese companies for the purpose of promoting exports.

Infrastructure and social welfare contribution

Local governments in China often facilitate the infrastructure development for their industrial constituencies and subsidize some companies by chipping in to companies' social welfare plans. The latter could be understood as a form of labor cost subsidization. As a socialist society, China relies on governments at all levels to play an important role in building the social safety net, including health care, pension, schools, etc. Besides legal requirements, local governments sometimes use additional social welfare contributions to industrial parks and/or companies in their jurisdictions as an incentive for economic development. For example, Wuxi municipal government officials told story about the government used to pay for part of the social security and pension fund of a star solar company in Wuxi[52]. It indirectly lowered the company's labor cost. In other cases, the welfare subsidies are used to attract and ***mobilize human resources.*** For example, still in Wuxi, world's leading PV scientists and entrepreneurs who chose to work in the city were rewarded with a free car, an apartment and a lab or subsidized factory infrastructures[53].

Local governments also subsidize infrastructure such as public transit systems linking the industrial parks and residential areas of the town, standardized ready-to-move-in factory space in industrial parks, or even schools for industrial park employees. One

[52] Interviewee #90, #91, #92
[53] Interviewee #91

interesting example is the international school in Trina Solar Industrial Park in City of Changzhou in Jiangsu Province. Trina is the world's largest solar PV producer. It continues to expand its global footprint and benefits from having a global workforce. Its research and development strength has grown significantly after recruiting a renowned Belgian PV scientist as its CTO. However, during it international recruiting process, Trina noticed that one of the biggest concern for their foreign employees was their children's education. To ease the concern, Trina built an international school right in the heart of the industrial park with financial and administrative assistant from Changzhou municipal government. The school does not directly affect the production cost at Trina in any positive or negative way, but it increases the company's attractiveness among potential foreign recuritees and allows the company to build a better workforce, which contributes to their long-term competitiveness.

4.3.5.2.2. Impacts and Consequences of Government Subsidies

There are a lot more examples of government subsidies and incentives given to the solar PV industry, especially and manufacturing sector, in the 2000s. However, the generous government supports have caused controversies and led to countervailing claims coming from E.U. and the U.S. Nowadays, subsidies and incentive programs targeted the PV industry have shifted from the manufacturing sector to the deployment sector. The reasons for this shift are two-fold.

First, the maturation of the manufacturing sector allows companies to be financially more self-sustainable. Second, the Chinese industries and the industrial policy-making body in the government learned a lesson from the first decade of the 21st century that subsidizing and incentivizing the industry development is not without consequence, especially when the decisions to subsidize and incentive were not made in a rational way.

The institutional underpinning that caused the turmoil in the PV manufacturing sector between 2012 and 2014 was the single-minded pursuit of economic growth. Maintaining a fast growing economy has become the commanding height of Chinese governments at all levels. The flawed government official promotion system in China places an overwhelming weight on officials' economic development performance. As a result, local government officials pay a disproportionally large amount of attention to GDP growth and job creation numbers in his or her tenure, at the cost of almost everything else. Since solar PV manufacturing sector is a perfect candidate for economic development, considering the GDP, jobs and trade surplus it generates, many local governments chase after the solar PV industry. They would do all they can to first attract PV manufacturing firms to locate in their jurisdictions and then ensure the continuous operation of the factories during their tenures.

Two problems follow such logic. First, the officials have no incentives to safeguard the common sense market entrance screening procedures, especially when there were no well-written rules about it. They become addictive to creating short-term economic growth and captive to companies that can fulfill that prospect. Second, when companies that received government supports ran into trouble during the industry downturn, local officials had a hard time letting them go because if the factories shut show, GDP growth and job creation would slow down too, which would directly affect their career advancement. The skewed incentive structure created an inherent tension between the central and local governments. When the industry was in a good shape, the incentives were aligned between the central and local governments: they all wanted the industry to flourish. However, when the industry ran into trouble, there was a divergence in reactions from the two sides. Local governments were attached to the particular firms located in their jurisdictions; they wanted to protect them from going out of business. In contrast, the central government's goal was to ensure the survival of the whole industry, not necessarily particular companies.

Nevertheless, with local GDP and their own career advancement on the line, local officials in many cases were unwilling to follow the central government's guidance to restructure the industry. This inherent tension between the two levels of governments created a vicious circle. On the one hand, the central government issued new industry standards, tightened its policy and financial supports for existing firms, and drafted regulations to raise the bar for new market entrance. The changing policy and financial environment made it harder for the troubled PV firms with low qualifications to make any move. Some were even forced to exit the market. However, on the other hand, local governments often bypassed the central government's guidance and continued pledging policy and financial supports to troubled PV firms. Unfortunately, their attempts were proven futile given the more powerful macro policy landscape to restructure the industry. Much of the local governments' effort to inject financial resources into bailing the falling solar PV firms turned out to be a waste of money.

Nonetheless, the trade wars with the E.U. and U.S. over subsidies and the punitive measures imposed on Chinese panels did ring an alarm to Chinese policymakers. They are becoming more and more prudent in using subsidies and incentives in not only the PV manufacturing industry but also the manufacturing sector as a whole. Overall, government subsidies and incentives certainly mobilized resources for the solar PV industry in China, but the repercussions from them were also damaging to the industry.

Blocking mechanism 4.4: Local governments' entrenched ties with the PV manufacturing sector led to irrational economic decision-making in the utilization of subsidies and incentives, which subjected the industry to excess capacity issue and trade frictions.

4.3.5.3. PV Deployment Policies

The solar PV manufacturing sector and the deployment sector are closely linked. The former make the products that the latter use to generate emission-free renewable electricity. The whole premise for treating the PV manufacturing sector as a sector of the future is not because of the inherent virtue of the PV manufacturing processes but because of the clean electricity generated from the PV panels holds the promise to solve some of the most pressing environmental issues face by mankind. In other words, solar PV manufacturing is not an end but a means to a new energy future.

The PV manufacturing sector and the deployment sector are mutually dependent. The latter relies on the former to provide solar panels; and the former depends on the later to sell their products. In fact, deployment policies are crucial in creating market demand for the manufacturing sector (***market creation***). If use wisely, it can create a "demand-pull and supply-push" virtuous cycle (Brown, Chandler, Lapsa, & Sovacool, 2007).

Not only PV manufacturing and deployment sector are intertwined, they also transcend national boarders. In today's globalized world, PV manufacturing and deployment are global games where manufacturers can choose to sell their products to either domestic or overseas customers, and consumers have the freedom to select from a variety of domestic and international brands.

The Chinese PV manufacturing industry is the beneficiary of this global PV market. The boom in global PV deployment started in Germany in the early 2000s with the first of its kind feed-in tariff (FIT) program, followed by similar programs in other European countries like Spain, Italy and France. FIT is a deployment incentive that offers a guaranteed buyback price to solar electricity generator for a long period of time (15-25 years). It provides price and market certainty to solar adopters in order to incentivize deployment. The renewable portfolio standards (RPS) implemented in a number of U.S. states also expanded the market for solar PV (Marilyn A. Brown, Gumerman, Sun, Sercy, & Kim, 2012). RPS requires a certain percentage of electricity generation coming from renewable sources. States like California, New Jersey, North Carolina, etc. also include a solar carve-out that mandates a minimum level of solar adoption within RPS. Demands for solar panels created by these deployment policies were largely met by cheaper products from China. 60% of the solar panels sold in 2012 were from China (GTM Research, 2013). The fast capacity expansion of the manufacturing capacity in China in the first decade of the 21st century was fueled directly by the booming overseas market. Continuous capacity expansion created economies of scale and fostered the maturation of domestic Chinese PV supply chain, which among many other factors, further cut the cost of Chinese solar PV. Consequently, cheaper Chinese PV lowered the cost of solar electricity in the overseas markets, increased the competitiveness of solar as a source of electricity supply, and spurred a greater diffusion of solar. Ultimately, the deployment policies overseas created a virtuous cycle (Figure 4.3) that benefits both the solar manufacturing in China and the solar deployment sector overseas.

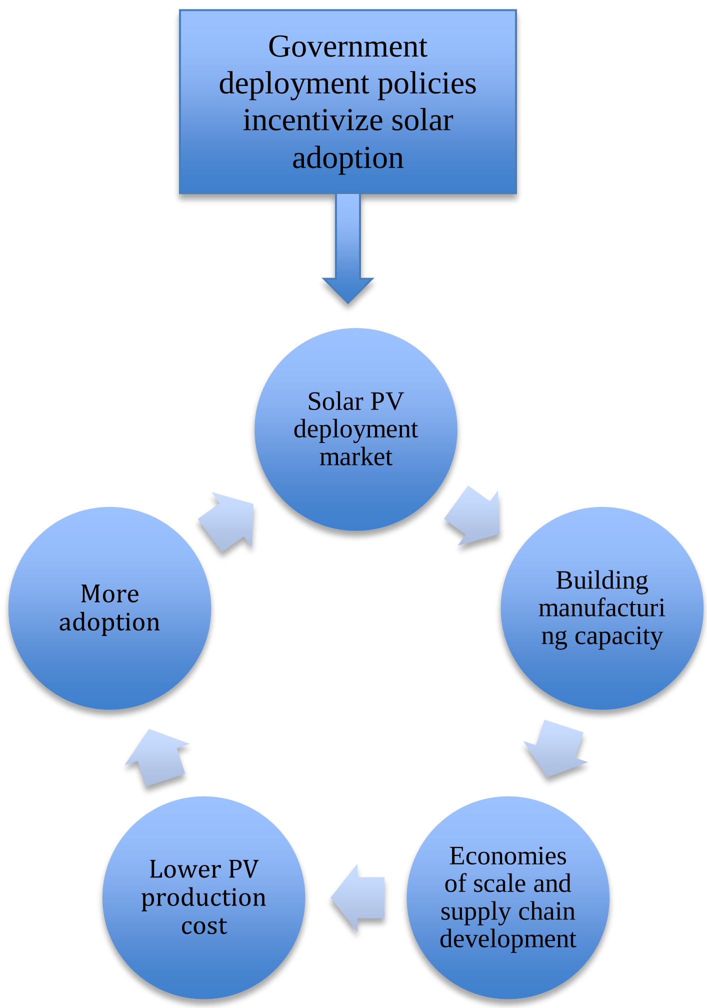

Figure 4.3. Virtuous cycle of solar PV manufacturing and deployment

This virtuous cycle highlights a key function of deployment policies in the development of the solar PV industry, which is it spurs ***positive externalities***. Deployment policies do not only promote the adoption of solar PV as a form of electricity generation, they also ***create markets*** for the PV manufacturing sector and provide necessary condition for future manufacturing capacity expansion.

Nonetheless, the geographic mismatch between the deployment market and the solar PV supply can be problematic. The fact that their taxpayers' money was spent on buying Chinese products and fueling the expansion of the Chinese PV industry did not sit well with politicians and PV manufacturers in Europe and the U.S. Protective trade measures were taken. Anti-dumping and countervailing allegations were brought forward in both places and the final rulings restricted the export markets for Chinese PV manufacturers. The Chinese PV manufacturing industry felt the immediate impact of the trade rulings; the large manufacturing capacity it built in anticipation of a growing overseas market suddenly became excessive. A number of Chinese manufacturers went out of business.

However, the industry was saved from a disastrous collapse in part by the deployment policies rolled out by Chinese government. Compared to its the world's largest PV manufacturing capacity, China's domestic PV deployment had been incommensurable for a long time. During the peak of its export era, 90% of the solar panels made in China in 2012 were sold overseas, domestic demand constitutes only 10%. Before 2013, there were two major distributed solar incentive programs: the Solar Roofs Program and the Golden Sun Demonstration Program (Exhibit 3 in Appendix C provides detailed description of these two program). By the time the two programs ended in 2013, 3.38GW of distributed solar had been installed as a result of these two programs (Chinese Academia of Sciences, 2014).

However, critics pointed out that the capital investment-based subsidies did not incentivize developers to pay attention to project quality and final electricity generation. In 2013, Chinese government replaced the Golden Sun and Solar Roof Program with a nation-wide FIT program. The FIT was first implemented in 2007, shortly after the Renewable Energy Law of 2006 went into effect. Initially, it was only implemented in the power sector via a bidding process. After four years of experiment, NRDC set the first nation-wide FIT for utility-scale solar PV at ￥1.15/kWh ($0.18/kWh) and ￥1/kWh ($0.16/kWh) for solar projects that complete before and after December 31, 2011. Starting from 2013, both distributed and utility-scale solar were included in the FIT scheme. The term of the contract is usually 20 years. Table 4.8 summarizes the current FIT scales in China.

Table 4.8 FIT for Utility-scale and Distributed Solar Since 2013

Solar Resource Area	Utility-scale Solar ￥/kWh ($/kWh)	Distributed Solar ￥/kWh ($/kWh)	
		Onsite Consumption	Utility buyback
I: Excellent Solar Resource	0.90 (0.14)	Retail rate + 0.42 (0.07)	Production cost + 0.42 (0.07)
II: Good Solar Resource	0.95 (0.15)		
III: Fair Solar Resource	1.00 (0.16)		

For distributed PV, many provincial and local governments in China also offer their own subsidies. In the most extreme case, distributed solar PV in City of Xiuzhou in Zhejiang Province enjoy five levels of incentives. In addition to the FIT offered by the central government, there are provincial level, city level, and Xiuzhou-specific special provincial level FITs, plus the capacity based investment subsidy offered by Xiuzhou Municipal government. By the third quarter of 2015, 15 out of the 32 provincial level jurisdictions offer additional FITs and investment subsidies to distributed PV[54].

[54] Interviewee #67, #81, #82.

Besides FITs, grid companies are required by the Renewable Energy Law of 2006 to develop grid connection agreements with utility-scale solar plants to purchase all their generations. Similarly, mandated purchase also applies to excess electricity produced by distributed solar generators. The mandated connection and purchase policies meant to reduce market uncertainties for solar projects and further spur the deployment. In 2013, in conjunction to the reform of FITs, the central government issued a few official documents to increase the enforcement of mandated connection and purchase.

It is hardly a coincident that multiple solar regulations, incentive programs, and official documents were issued in two time periods, 2009 and 2013. The Solar Roofs and Golden Sun Program were established to jumpstart China's domestic deployment market in wake of the 2008 global financial crisis, an event which caused many European countries to temporally cut back them solar subsidies. Furthermore, the rollout of the nation-wide FITs program that covers both utility-scale and distributed solar, together with the emphasis on measures that provide certainties to solar generators in 2013, were in response to the sharp decline in PV export to European and American market due to the trade conflict. The timing of the events and the intentionality behind them is a clear sign that deployment policies were used not only as a way to spur solar energy adoption but also as means to expand domestic deployment market for Chinese PV manufacturers in order to absorb the excess production capacity.

In summary, Chinese PV manufacturing industry benefited from having access to three largest global markets during their fastest growth periods: the European market between 2000 and 2012, the U.S. market between 2005 and 2012, and its domestic market from 2009 till present. The strong demand created by European and American solar deployment policies partly provided an environment for Chinese manufacturers to grow their production strength and gain dominance in the global market. When that strategy ceased to work due to the trade conflicts, solar deployment policies promulgated by Chinese government rescued the PV manufacturing industry by unleashing the potential in the previously untapped domestic market.

Driving mechanism 4.12: Deployment policies in Europe, the U.S., and China drove the creation of solar PV markets in the respective regions, which consumed the produce made by Chinese solar PV industry and enabled the formation and revolution of its economies of scale style development.

4.3.5.4. Loose Labor and Environmental Regulation

China has loose labor and environmental regulations compared to developed nations. The "hardworking" culture discussed earlier is in part fueled by the lack of labor rights protection. Salary-based employees are rarely compensated for their overtime. Hourly-based factory workers are usually not compensated with a pay differential for their night and weekend shifts as long as it is within the total amount of working hours allowed by the Chinese labor law. In comparison, the same practice would not be allowed in western developed countries. Looser labor regulations in China make it easier and cheaper to mobilize workers. The output of Chinese production lines is high while the cost of labor is lower as a result, but they come at the price of the pay and work-life balance of the workers.

Looser environmental regulation is another area where Chinese firms, especially silicon and wafer manufacturing firms, had taken advantage. According to interviews with a high level executive of GCL Poly[55], the world's largest polysilicon and wafer producer, China supplies over 70% of the world's wafer demand and over 50% of the world's polysilicon demand in part because of the affordable energy cost and less stringent environmental regulations compared to countries like Germany, Japan, and the U.S. The process to produce polysilicon and wafer requires a lot of energy and emits large amount of pollutants. Both the command-and-control type of environmental

[55] Interviewee #74

regulations that require polluters to install pollution control equipment and market-based regulations that allow polluters to explore cheaper ways to reduce emissions would inevitably impose compliance cost to heavy polluters like polysilicon or wafer producers. They add an additional layer to the production cost. Furthermore, in countries like Germany and some states in the U.S., part of the costs to comply with stringent environmental regulations like the EU Emission Trading Scheme (EU ETS) and California's AB 32 are internalized into the energy costs, resulting in higher electricity prices. In China, air and water pollutant emission standards are set at a lower level compared to developed countries, and the social cost of emissions has not been internalized into the electricity price yet. Therefore, the electricity cost is cheaper in China compared to those countries and regions. On top of the lax environmental regulations, the existing laws in China are not well enforced, leaving loopholes that can be exploited by emitters.

Looser environmental standards and weak enforcement create a "low-cost" business environment that is favored by industries with heave emissions. This phenomenon is described in literature as "race-to-the-bottom" or the pollution haven hypothesis (Bommer, 1999). Although it has not triggered the overseas polysilicon and wafer producers to migrate their production to China (due to other business concerns), it certainly gives domestic Chinese players a cost advantage.

Chinese companies are well aware of the fact that their operations in China benefited from the loose labor and environmental standards. In an interview with the CFO of a Tier 1 Chinese company, he listed more stringent labor and environmental regulations as one of the factors that may lead the company to shift their operation in China to countries that have even less stringent regulations[56].

However, things are changing in China in the environmental field. The notorious air quality has prompted the government to take actions on controlling pollutions. A suite

[56] Interviewee # 96

of actions has been taken to curb energy consumption and reduce the amount of emissions produced during the energy production process. The most anticipated change of all is China's upcoming greenhouse gas emissions cap-and-trade program, which would impose emission upper limits to heavy emitters including the power sector and most manufacturing industries. Once the cap-and-trade program becomes effective, it will increase the cost of production for firms in the solar PV value chain in China, and level the playing field between China and countries with stringent environmental regulations, although it will also make outsourcing production to lower wage country with looser environmental regulations more attractive to Chinese producers.

In addition to the nation-wide GHG reduction program, the solar PV manufacturing industry also faces a new set of environmental and energy productivity requirements put out by MOIIT in its Solar PV Manufacturing Industry Standards of 2013 (Ministry of Industry and Information Technologies of China, 2013). The standards put forward specific energy productivity goals (in kwh of electricity/output term) tailored to each link of the PV manufacturing value chain. Only companies that meet the requirements are allowed to stay in the industry. The Standards also specified the environmental regulations that companies need to comply, which cover the following areas: air and water quality, odor, hazardous waste, solid waste and noise. However, the Standards do not have any legal power to enforcement the compliance.

In summary, lax labor and environmental regulations and loose enforcement have historically given the Chinese PV industry advantages in factory-wise productivity and cost. Nevertheless, as China is taking actions to improve its environmental quality and rise labor standards, more stringent regulations are expected to be implemented and they will shrink the advantages that Chinese firms use to have.

To summarize, this section explored 15 factors that are found by this study to have impact on the competitiveness of Chinese solar PV manufacturing companies. They span across a wide spectrum of categories, from firm specific strategies to industry-wise agglomeration economies, to macro level factors such as culture, resources, and national policies. It has to be concluded that it is impossible to pin the cost advantage of the solar PV industry in China on one factor. Rather, just like what the quantitative analysis has found, it is a combination of a set of interconnected factors that shape the industry. The factors discussed above either historically or currently contribute to the continuous reduction of the solar PV production cost, although some of them build a long-term advantage, such as economies of scale, supply chain clusters, modern management methods, etc., whereas others are unsustainable forces, for examples loose environmental regulations, cheap labor cost, etc.

4.4. Conclusions

This chapter combines quantitative analysis with on-the-ground fieldwork to understand the sources of competitiveness of the solar PV manufacturing industry in China. The quantitative analysis suggests that a combination of low electricity cost, low R&D investment, low cost of debt and low cost equity lead to lower solar panel production costs among Chinese players before 2010; vertical integration, module capacity and tax rate are mixed show no consistent causal pattern vis-a-vis low PV production cost. However, in the post-2010 era, the higher level of vertical integration consistently co-exist with the four variables identified in the pre-2010 era as factors that cause low production cost in China. Although evidence on module capacity in the same era is not as consistent as the other five variables, whenever the presence of large module capacity is found to have an impact it always leads to low solar panel production cost in combination with low electricity cost, low R&D investment, low cost of debt and low cost equity, and high level of vertical integration. Different causal patterns before and after 2010 suggests that there is a tipping point for the impact of manufacturing scale on PV panel production cost. As PV panel production truly reached a large enough scale around 2010, vertical integration and module capacity became meaningful causal factors for low cost production around the same time. It indicates that "economies of scale" is not an abstract concept. Rather, it takes a critical mass of production capacity in order to realize the benefits associated with economies of scale.

Due to data availability, many intangible factors were not explored in the quantitative analysis, but they were not left unexplained. Instead, drew from rich interview data, this dissertation developed a typology that categorize the potential sources of competitiveness of the solar PV manufacturing industry into five groups that cover both the micro and macro aspects of the industry and the political economy it embedded in. This study further examined their impact of these 15 factors on the development and maturation of the PV manufacturing industry in China.

First and foremost, policies played a big role in shaping the industry. The national vision and industrialization strategy for the PV manufacturing industry promoted by the Chinese central government since the 10th FYP brought the industry to a fast track for development. The vision and strategy established economies of scale and supply chain development as two main principles and later added innovation as the third one. The underlying theory behind the first two principles is that they lead to the formation of agglomeration economies, which can lend advantages to firms, the industry and regions where the industry locates. In fact, the principles structurally shaped the industry and enabled the building of the world's largest PV manufacturing capacity and a highly concentrated supply chain that is unmatchable elsewhere. Resource factors like skilled labor, good infrastructure and easy access to capital certainly created a friendly environment for manufacturing. Besides the macro-level policy and structural factors, at the micro-level, Chinese companies are flexible, and willing to tap into both low-key and highbrow strategies such as process innovation and modern scientific management approaches to build their competitiveness. In addition, cultural factors such as pragmatic mindset, work ethic and the unabashed pursuit for low cost are just as salient as the tangible factors in making China a unique place for solar PV manufacturing.

However, the same set of factors, when poorly utilized, could also impede the development of the industry. The same factors that are instrumental in creating the cost competitiveness among Chinese firms, such as pragmatism, the determination to continue to drive down cost have, to some extent, diverged the attention that could otherwise have been paid to scientific and technological innovation and product quality improvement. Today's Chinese solar PV industry, despite its lion share of the global PV market, is still known as the provider of affordable but low-end solar PV products. Many companies struggle to transcend their business to the higher end of the solar PV value chain because of the weak innovation capacity and the lack of desire to carry out long-term, risky and R&D-laden projects. In addition, the overshoot in manufacturing capacity expansion fueled by irrational policy decisions made by local governments – such as local free cash grants, imprudent preferential lending and tax breaks, etc –contributed to the "quantity over quality" culture, resulting in trade conflicts with its major trading partners, rendered a good portion of the manufacturing capacity in China excessive.

In conclusion, Chinese solar PV manufacturers' market competitiveness is a result of a suite of factors that work in conjunction with one another. Both quantitative and qualitative evidence suggests that economies of scale and government subsidies are causally related to the low cost production of the industry. Qualitative analysis further uncovered the nuances embedded in economies of scale and how it and supply chain development mutually reinforced each other to create agglomeration economies. Government assistant subsidies and incentives had shown to be useful in short-term at the initial stage, but are problematic in the long run. However, government policies can be helpful in setting an industrialization vision and strategies as well as in fostering domestic demand for the manufactured good. This study also finds that contextual factors matter. The working culture, the pragmatic mindset, as well as the loose environmental and labor regulations are all part of the unique characteristics imprinted by the development path that the country has taken and should not be overlooked. Finally, more investment into

R&D was not found to be a causal factor leading to low cost production in China. Quite to the contrary, the opposite was found to be true by the quantitative analysis. However, qualitative analyses show that Chinese companies can strengthen their long-term competitiveness by conducting scientific and technological innovation that does not only contribute to low-cost production but also improve product quality and conversion efficiency. .

CHAPTER 5.

THE SOLAR PV SUPPLY CHAIN IN CHINA

5.1. Introduction

The most quintessential characteristic of China's PV manufacturing industry is its supply chain. It has unmatchable size, density and robustness, and it has become a key enabling factor for the continuous productivity improvement and solar panel production cost reduction discussed in Chapter 4.

Scholars have been studying regionally compact industries and their supply chains for a long time. They have found that industrial clusters that connect manufacturing firms and their suppliers create agglomeration economies and they strengthen firms' competitiveness and spur regional economic development (Clark, 2013; Gordon & McCann, 2000; Sturgeon, Van Biesebroeck, & Gereffi, 2008; Tan, 2006). Comparing to industries such as the photonic and automotive industry –the supply chains of which have existed for decades – the history of solar PV supply chain in China is short. It started shortly after the solar PV manufacturing industry began to gain traction in early 2000s. But just like the manufacturing industry, the supply chain developed rapidly, partly because of the unprecedented market opportunity and a suite of national policies and industrialization strategies in China. An intricate relationship was established between the supply chain and the PV manufacturing industry. They mutually reinforced each other's growth and maturation. In an era where China's low labor cost is undercut by Southeast Asian countries, a robust supply chain gives Chinese solar panel manufactures a unique advantage.

The supply chain development does not only interact with the manufacturing sector, it is also closely related to the innovation system. The development and maturation of China's domestic solar PV supply chain is as much a history of manufacturing innovation as industrial clusters development. As China moved from almost completely replying on imported equipment for cell manufacturing to 85% self-reliance as of 2014 (CCID, 2015a), R&D in tooling, materials, and cell and module production played a big role. Nevertheless, China's domestic PV supply chain is only as strong as its innovation capacity; many problems that trouble the innovation system (detailed in Chapter 3) also impede the further growth of the supply chain.

There has been very few in-depth studies of China's solar PV supply chain. In 2013, a group of researchers from the U.S. National Renewable Energy Laboratory concluded that supply chain is the single most important reason that panels made in China are cost-competitive (Goodrich et al., 2013a). However, their approach used a very limited sample size (2 Chinese companies) and relied heavily on modeling and simulation instead of contextual knowledge. To fill the void, this chapter means to build on deep on-the-ground knowledge gained from intensive fieldwork conducted in the Chinese solar PV manufacturing industry to accomplish five tasks.

It will first tell the history of the supply chain development, and uses it to explain the interconnection between policy and markets. It will then dissect the characteristics of the today's supply chain and analyze its strengths and weaknesses. The third task is to provide a thorough argument for why building a domestic supply chain is central to the competiveness of a manufacturing industry. Fourthly, a case study of the 48th Research Institute, a leading Chinese solar PV manufacturing tooling supplier, will bring the first three points together and contextualize them. Finally, policy recommendations in terms of using supply chain to enhance manufacturing sector competiveness will be provided.

5.2. History of China's Solar PV Supply Chain

China's solar PV supply chain grew out of its manufacturing system. When Chinese PV manufacturers first selected places to build factories in the early 2000s, supply chain was an important factor that they took into consideration, along with other factors such as cost of labor, labor skills, local business environment, etc. The presence of local suppliers would certainly boost the chance of a region in getting a factory deal.

5.2.1. Pre-2000 Era: Emergence of the first generation, non-solar specific suppliers

There was practically no solar PV supply chain before 2000. Most of the so-called solar PV suppliers back then did not supply to the solar industry exclusively. They first developed as material and equipment suppliers to industries that preceded solar such as the home appliance industry (such as electric wire and ribbon suppliers, etc.) and the building industry (such as glass suppliers). When the solar PV industry started to boom these material and equipment suppliers seized the opportunity and began to tailor their production to PV manufacturers. For the PV manufacturing industry's perspective, the its initial development benefited from a supply chain that was first built for non-PV manufacturing industries. In a broader context, the industrialization in China since the late 1970s built a robust manufacturing infrastructure in the country, which includes a large number of small and medium enterprises (SMEs), especially in the Yangtze River Delta (YRD) area (Jiangsu-Zhejiang-Shanghai) and Pearl River Delta (Guangdong-Fujian) area. They function as material and equipment suppliers to large manufacturing companies. These SMEs are often started by local entrepreneurs in the so-called township and village enterprises form. These entrepreneurs engaged in their ***entrepreneurial experimentations*** and often offer products that are generic enough to be used by multiple industries (Putterman, 1997; Weitzman & Xu, 1994). For examples, materials needed in solar module production, such as electric cables, glass, aluminum frame, etc, are also needed in the manufacturing of consumer electronics, furniture, and so on. Therefore, different manufacturing industries often share common suppliers. The merits of such model include maximizing supply chain efficiency by avoiding building redundant suppliers and increasing supply chain resilience with versatile suppliers.

5.2.2. 2000-2012: Co-development of solar PV manufacturers and solar-specific suppliers

The existence of the suppliers was appealing to a good number of solar manufacturers. When the first generation Chinese solar PV manufacturers like Suntech, Trina, and Canadian Solar first started to build their factories in the early 2000s, they all took advantage of this shared suppliers model in the YRD area and consequently, they form the initial solar PV manufacturing cluster. The emergence of this cluster in turn has had a profound ***influence on the direction of search*** of existing and future suppliers and shaped the supply chain development in the following two ways.

First, the sizable demand from these companies created a big market for existing local material and tooling suppliers. As the Chinese solar industry entered it fast growth period during 2005-2010, many local suppliers pivoted their business from supplying to traditional manufacturing industry in the region to focusing more or even exclusively on the emerging PV industry. For example, Flat Glass in Jiaxing, Zhejiang Province started as a generic glass manufacturer primarily for the construction industry. After a number of solar panel manufacturers opened their factories in its surrounding area, Flat Glass began to produce solar-grade glass in 2006 and supplied them mainly to PV producers in the YRD area (***influence on the direction of search)***. As of 2014, Flat Glass is the world's largest solar-grade glass manufacturer, and their market expanded from the regional market to the globe. SME suppliers' strategy to pivot to the solar PV industry was the first step towards building a solar PV supply chain. They co-located and co-developed with their customers.

Second, the explosive growth of the PV manufacturing industry in the mid 2000s created a market for *new* material and tooling suppliers. As discussed in Chapter 4 Section 4.3.5.3, Chinese PV manufacturers seized the market opportunities created by pro-renewable legislations such as German Renewable Energy Act (EEG), the Royal

Decree 436/2004 in Spain, and the state level Renewable Portfolio Standards in the U.S. and exported a large amount of affordable solar panels overseas. At the initial stage of solar PV deployment in all markets, the high panel cost was the biggest barrier. Consumers and developers in European and North American markets looked for cheaper panels to improve the economics of their projects. Chinese panels were attractive given their prices. As a result, Chinese PV manufacturers saw large demand from overseas. They responded by quickly ramping up their production capacity to keep up with the demands.

The strong growth of the PV manufacturing sector demanded an equally strong domestic supply chain. If the first generation suppliers were what attracted a large number of solar PV producers to locate in the YRD area, then the entrance of new suppliers was the reason that they stayed and grew to be the industry leaders, because with the new suppliers a *complete* solar PV supply chain was finally formed. The newcomers contributed to the buildup of a complete supply chain in two ways. First of all, they filled the void left by the first generation suppliers. For historical and technical reasons, the first generation suppliers could not meet all the materials and tooling demand of PV manufacturers. This is partly because the YRD area historically has strong light industries but the solar PV manufacturing requires equipment and certain materials such as silicon and wafer that have to come from heavy industry in other regions in China or even from overseas. In addition, many first generation solar PV suppliers simply did not have the technical ability to meet the material and tooling demand from their customers. However, whenever there is a void, there is an opportunity. A new generation of solar PV-specific suppliers came to the marketplace to fill the blank in the late 2000s.

GCL Poly, the current world’s largest polysilicon and wafer producer, is the poster child of the second-generation solar-specific suppliers. Before GCL Poly entered the solar market in 2006, Chinese PV producers relied mostly on importing polysilicon and wafer (two main types of feedstock for producing silicon-based solar panels) from

Germany and the U.S. This is because polysilicon and wafer production are capital-intensive processes that also have high knowledge and technical requirements; few Chinese companies had both the technical and financial capabilities to do business in this area. However, the public listing of Suntech, Yingli and Canadian Solar at New York Stock Exchange in 2005 and 2006 spurred a wave of manufacturing capacity expansion of in the YRD area. Market demand for polysilicon and wafer soared and the price for the former was pushed up to as high as $500/kg at one point. Against such backdrop, GCL, a former non-stated owned power company, formed GCL Poly and entered the upstream solar supply chain. It invested a large amount of capital to mastering the technical knowledge and know-hows of silicon production ***(knowledge development and diffusion)*** and quickly established itself as a significant player in the silicon and wafer business. Today, GCL Poly has its main polysilicon production facility in Xuzhou in Jiangsu Province, and 3 wafer production plants in Changzhou, next to Trina Solar (the world's largest solar PV producer), 3 more in Suzhou, next to Canadian Solar (a global top 5 solar PV producer), another 3 in Xuzhou next to its own polysilicon facility, and 3 in Taicang in Jiangsu Province, 50 miles northeast of Suzhou. GCL Poly's factory locations reflect its strategy to form a strong connection with PV manufacturers in the YRD area. The result is that both GCL Poly and its local customers grew significantly since the mid 2000s. GCL Poly became the world's largest polysilicon producer in 2011, the world's largest wafer producer in 2012, and has remained at the crown till today (Q4 of 2015). At the same time, its local customers have seen their cell manufacturing capacity grow from just over 500 MW in 2006 to near 17,000MW by the end of Q2 of 2015, a more than 30-fold increase.

Flat Glass and GCL Poly are two snapshots of how a fast-growing industry can drive the development of its supply chain and in turn further its own growth. There are many examples like them in China's solar industry. The bottom line is that the market for solar material and tooling suppliers is large and the first generation generic suppliers were not able to fulfill all the demand. The market opportunity invited a large number of newcomers to enter the industry in order to fill the gap left by the incumbents at the same time the incumbents also continue to solidify their position in the industry. By the early 2010s, the supply chain concentrated in the YRD area reached a state that was complete and robust.

Driving mechanism 5.1: The booming solar PV manufacturing industry created market opportunities that did not only attracted generic suppliers but also spurred the birth and growth of solar-specific suppliers, many of which developed specialties that filled holes in the supply chain. As a result, the supply chain grew bigger and more complete over time. (Illustrated in Figure 5.1)

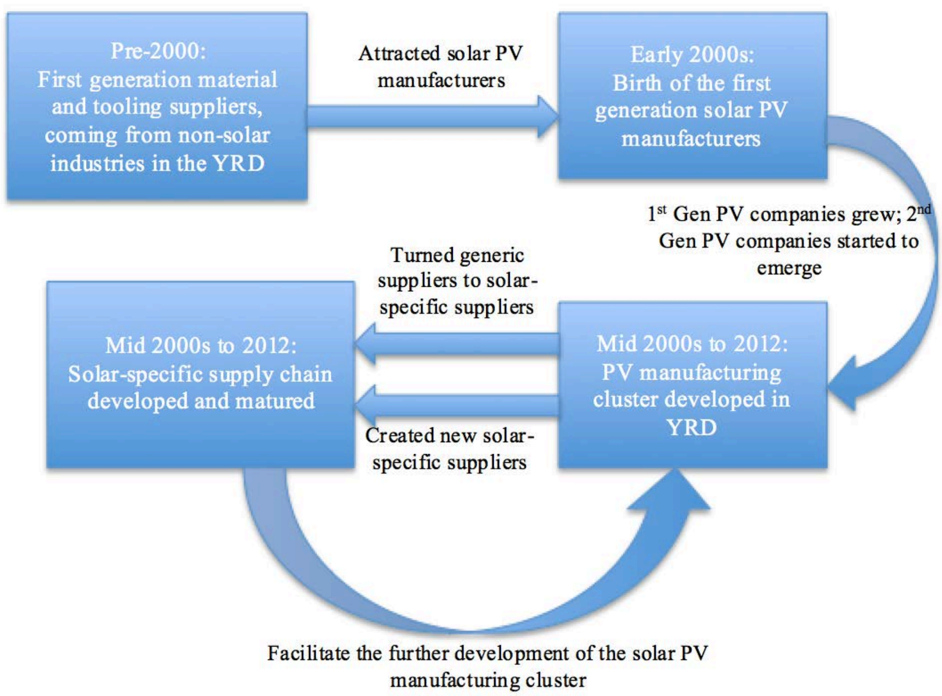

Figure 5.1 Mechanism of Solar PV Supply Chain Development in the Yangtze River Delta (YRD) Area

5.2.3. 2012 – Present: Trade wars and government orchestrated industry restructuring

The explosive growth of the PV manufacturing sector in China was not free of controversy. American and European PV manufacturers have alleged that Chinese firms sell their products at prices below their production costs, which led to the anti-dumping investigation initiated by the U.S. (U.S. Department of Commerce International Trade Administration, 2012a, 2014b) and the E.U. (European Commission, 2013a). The Chinese government was also charged for unjustifiably subsidizing the industry in order to achieve price advantage, resulting in the countervailing allegation (U.S. Department of Commerce International Trade Administration, 2014b). Spearheaded by German solar PV manufacturer SolarWorld, the initial complaints were later co-signed by the Coalition for American Solar Manufacturing and the EU ProSun, both are solar industry association in U.S. and in E.U. respectively. They were brought forward to the U.S. Department of Commerce in October 2011 and the European Commission in September 2012.

In October 2012, the U.S. Department of Commerce (DOC) issued its final determinations on the first round of anti-dumping and countervailing investigations, alleging that Chinese firms and government had been engaging in both dumping and unjustifiably subsidization. U.S. DOC imposed import duties ranging from 18.32% to 249.96% on solar cells made in China (U.S. DOC, 2012a, 2012b). Following the U.S. DOC determinations, the E.U. trade commission issued similar findings, although the Chinese PV manufacturers were able to negotiate to change the penalties from tariffs to a price floor (0.56 Euro cents per watt minimum sales price) and a sales allowance that is equal to half of the European market size (European Commission, 2013a, 2013b).

The second round of anti-dumping duties that Chinese firms received from U.S. DOC's final determination in December 2014 ranged from 26.71% to 165.04%, and the countervailing duties were between 27.64% to 49.79% (U.S. Department of Commerce International Trade Administration, 2014a).

These restrictive trade measures limited the access to overseas markets and posted a big challenge to Chinese firms that rely heavily on exports. At one point, nearly 90% of the solar panels made in China were sold overseas (GTM Research, 2013). The manufacturing capacity expansion occurred during the booming years became excessive in front of the new market situation. A sever overcapacity issue plagued the industry. Firms that took on debt to build new factories were confronted with not only idled capacity but also financial difficulties to pay back loans. Many firms, especially SMEs went out of business. The solar PV industry standards issued by MOIIT further accelerated the restructuring of the manufacturing sector (for details, Section 4.3.5.4 in Chapter 4). As a result, large firms consolidated their power by absorbing SMEs; small and weak companies exited the market; and surviving companies shift their focus from singled-minded chasing low cost to paying more attention to product quality and innovation. Average R&D investment increased significantly since the structuring (See Table 3.13 in Section 3.6.3.3 in Chapter 3).

Table 5.1 shows the number of silicon-based and thin film solar PV producers over a five-year period. The rapid growth in number of players stopped in 2012. Approximately one third of the companies went out of business in 2013. Today, PV production capacity in China is highly concentrated among top tier players. In the silicon processing sector, top 10 Chinese producers accounted for 92% of the country’s total output in 2014; the top 5 accounted for 78%. Top 10 Chinese wafer producers made up 76% of China’s 2014 production; the top 5 accounted for 58%. Top 10 Chinese cell and module companies produced 53% and 55% of the products in 2014, respectively (CCID, 2015a).

Table 5.1 Size of the C-Si and Thin Film PV Manufacturing Industry

	2009	2010		2012		2013	
	Number of players	Number of players	Percent change from previous year	Number of players	Percent change from previous year	Number of players	Percent change from previous year
C-Si Cell	69	102	48%	156	53%	106	-32%
C-Si Module	349	476	36%	576	21%	385	-33%
Thin Film	42	49	17%	47	-4%	30	-36%

Sources: ENF Chinese Cell and Panel Manufacturers Survey 4th, 5th and Continuous Edition Analysis Report. The subscription to the ENF database came through the Stanford China Project.
Note: No survey was conducted in 2011.

The trouble with solar cell and module manufacturers unavoidably affected their suppliers, rendered them having to go through the same boom-and-bust cycle. Although MOIIT did not issue an industry standard regarding the PV material and tooling industries, suppliers felt the impact of the PV manufacturing industry standards vividly. PV manufacturers' demand for better product quality put pressures on suppliers to provide higher quality materials and more advanced tooling. Suppliers that could not meet the demand were also forced out of the market.

5.3. Main Characteristics of China's Solar PV Supply Chain

Three characteristics of the PV supply chain have shown to be essential to the competitiveness of the Chinese solar PV industry.

5.3.1. The supply chain is complete.

First and foremost, China has a complete supply chain with no missing links. This may sound very basic, but having a supply chain that covers every single material and tooling requirement is rare in today's solar PV manufacturing world. PV producing countries such as Germany, Japan, Malaysia, etc., for either environmental concerns or technical reasons, only have partial supply chain. For example, wafer production is a highly energy-intensive and polluting process. Companies located in countries like Japan and Germany, which that have limited energy resources and stringent environmental regulations, find it economically unattractive to produce wafer within their national border[57]. As a result, silicon-based solar panel producers in these countries would have to import wafers from mainly three overseas regions: China, the U.S., and Taiwan[58]. The heavy weight of wafer and the associated transportation cost put PV manufacturers in non-wafer production countries in a disadvantage position. Besides environmental regulations, technical barriers also prevent some countries from achieving a complete supply chain. Malaysia has recently become a hotspot for PV manufacturing as a few world's large PV producers such as the America-based Sun Power, China-based Jinko Solar and JA Solar, ect. built factories there. However, for the same reason that China did not have polysilicon production capability in the early 2000s, Malaysia today is not able to produce polysilicon domestically but rather relying on imports.

Compared to those countries, the PV supply chain in China is fully developed. Chinese PV manufacturers can source everything needed for a solar panel from domestic source. However, not every part of the supply chain is equally developed. Section 5.3.4 and 5.3.5 will further discuss the strengths and weakness of the supply chain.

5.3.2. The supply chain is robust.

The supply chain in China is not only complete, but it also has a large number of players at each link of the chain and together they create economies of scale. Figure 5.2 and 5.3 show a breakdown of the silicon-based solar PV supply chain in China in 2013, from raw material processing to balance of system components. The very first thing that stands out is the large numbers of suppliers at almost every step of the supply chain. The large number of suppliers inevitably creates market competition among themselves, which in theory would benefit PV manufacturers with lower cost, better product quality,

[57] Interviewee #57
[58] Interviewee #93

and more options. Table D.1 in Appendix D has a detailed accounting of the number of suppliers of each equipment and material type used in silicon-based and thin film PV production in 2013.

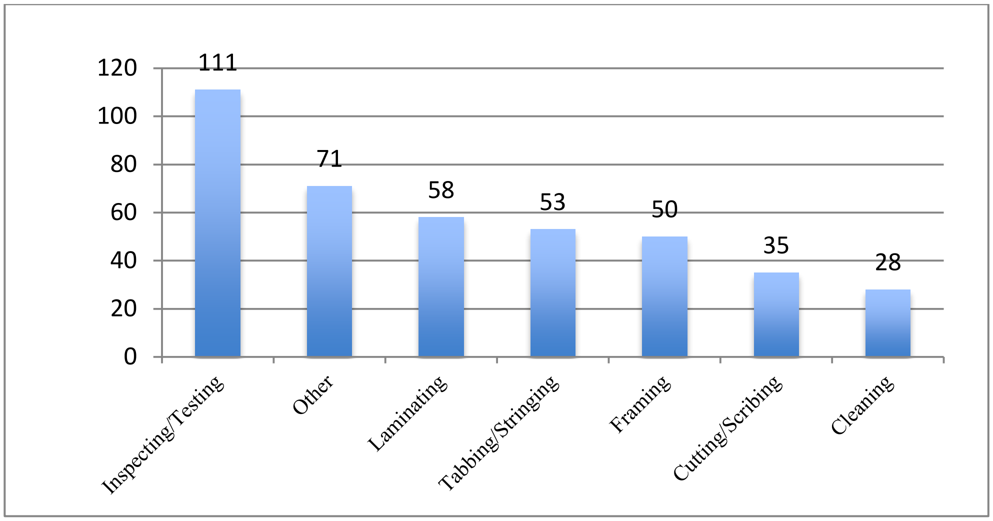

Figure 5.2 Number of Panel Assembly Tooling Suppliers

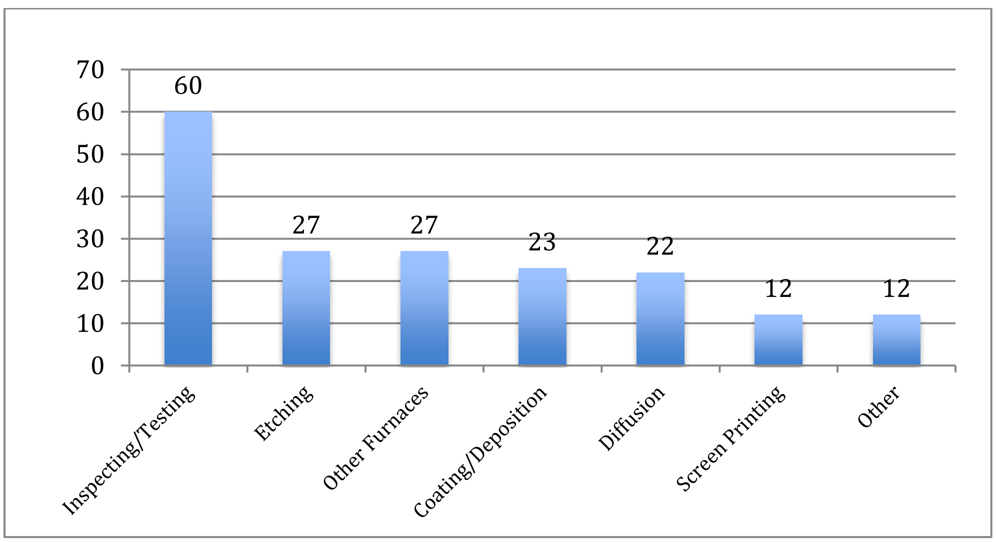

Figure 5.3 Number of Solar Cell Tooling Supplies

Source: ENF http://www.enfsolar.com/directory/equipment

Note:
The subscription to the ENF database came through the Stanford China Project.

5.3.3. China's solar supply chain is geographically concentrated

5.3.3.1. Solar PV manufacturing in the Yangtz River Delta (YRD) area

Global production networks (GPN) theory suggests that modern manufacturing benefits from having an interconnected global network that links designer, producer, suppliers and customers (Henderson, Dicken, Hess, Coe, & Yeung, 2002). Trans-national corporations (TNCs) can maximize their supply chain efficiency by embracing a web of global actors along the entire product life (N. M. Coe et al., 2008, 2004). Although there are examples of global production networks developing local production clusters due to external pressures, but motivations were not organic and innate (Sturgeon et al., 2008).

However, in the era of globalization, China's solar PV production activity is strikingly local. There are a large number of interconnected solar PV manufacturing firms and their suppliers in the YRD area, forming solar PV industrial clusters. Despite the powerful globalization trend, the clusters' ability to continue to attract firms in the same industry is eye-opening. Today, YRD is the most vibrant region for solar PV manufacturing in the world. It includes part of Jiangsu and Zhejiang Province and City of Shanghai. It is home to more than 30 GW of solar cell manufacturing capacity and over 36 GW of solar module manufacturing capacity, which accounts for 64% and 58% of China's total manufacturing capacity in 2014. They translate into 38% and 40% of the global total production (CCID, 2015b). Seven out of the global top ten solar cell and module producers have their factories primarily located in this area, and another four of the global top fifteen solar cell and module producers have a presence in the region (Table 5.2). They concentrate in an 8,000 square miles area around the delta area near where the Yangtze River meets the East Sea, forming a cluster of PV manufacturing capacity. Figure 5.4 is a map highlighting the PV cell and module producers located in the YRD area as of June 2015. Green diamonds represent solar PV manufacturing plants that are central to the development of the cluster. Table 5.3 summarizes their cell and module manufacturing capacity.

Scholars have found industrial clusters and the agglomeration economies they created are crucial in explaining some regions' economic competitiveness (Christopherson and Clark 2009; Gordon and McCann 2000; Munnich, Love, and Clark 1999; Porter 1990; Porter 1998). However, scholars are split in their media of analysis. Business school scholars tend to see the development of industrial clusters and regional economy through the lens of firm strategies and their networks. Government and regional policies and other resource factors such as labor are exogenous to their analysis (Porter 1998; Scott 1988). They treat the region simply as a space where business and industrial activities happen. In contrast, economic geographers explore both regional contextual factors and firm strategies and argue that place matters. It is through the interactions of firms and the regions they locate in that industry development and regional economic growth are realized (Christopherson and Clark 2009; Clark 2013; Scott and Storper 2007). They reply on each other and mutually shape the growth trajectory of one another. This study shares the second camp's view towards industrial development and argues that firm strategies (market) as well as national and regional policies (policy) are both part of an integral system. The next section analyzes how the solar PV industry and its supply chain in China develop at the intersection of market and policy. In Section 5.4 of this chapter, the solar PV supply chain in China will be used as an example to demonstrate how building a domestic supply chain can tremendously benefit a nation's industry and lend it global competitiveness.

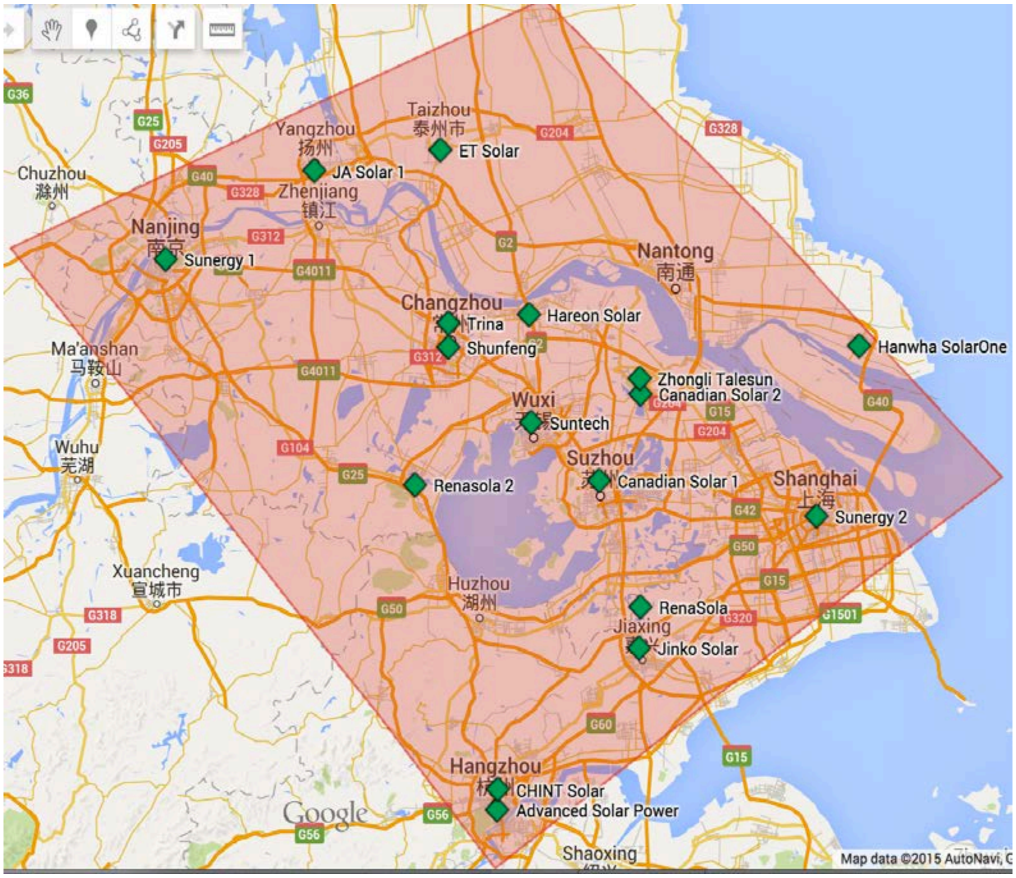

Figure 5.4 Solar PV Manufacturing Clusters in the Yangtze River Delta Region.
Sources: BNEF solar PV manufacturing plant database; Google Maps.
Note: The subscription to the BNEF database came through the Stanford China Project. The analysis of the data for the supply chain insight was done by the author as part of the Stanford China Project.

Table 5.2 Solar Cell and Module Production Capacity in the Yangtze River Delta Area in 2014*

Province	Cell Capacity (MW)	Module Capacity (MW)
Jiangsu	22,500	27,700
Zhejiang	7,800	8,675
YRD Total	30,300	36,375
China Total	47,000	63,000
YRD %	64%	58%

Table 5.3 Solar Cell and Module Production Capacity by Company in the YRD Area

2014 Global Ranking	Company	Cell Capacity (MW)	Module Capacity (MW)
1	Trina	2,680	3,850
3	Jinko	1,500	1,700
4	Canadian Solar	940	1,688
5	JA Solar	1,600	0
6	Suntech/ Shunfeng	2,510	2,400
8	Hanwha Q CELLS	1,162	900
9	Zhongli Talesun	900	1,000
11	Risen Energy	800	1,500
12	Renesola	265	1,150
13	China Sunergy	396	735
14	ZNShine	300	900

Source: BNEF company level factory capacity data
Note: The subscription to the BNEF database came through the Stanford China Project. The analysis of the data for the supply chain insight was done by the author as part of the Stanford China Project.

5.3.3.2. Solar PV Supply Chain in YRD, Where Market and Policy Meet

The industrial cluster of PV cell and module manufacturing is clearly shown in Figure 5.4. Besides, majority of the suppliers also locate in the YRD area, near their customers. They mutually depend on each other because market force requires them to do so. By locating close to a group of customers, the suppliers are able to reduce the risk of individual bad contract and be more attainable and flexible towards their customers' needs. From PV manufacturers' perspective, having a group of suppliers in close proximity give them more stable supplies, shorter deliver time, more product options, and more business certainties. They need each other to survive and thrive in the business.

However, market force does not work in isolation; it frequently interacts with policy and government planning. Take the city of Wuxi for an example. Wuxi is the home of Suntech Power, the former world's largest solar PV manufacturing company. Although Suntech went through a debt crisis in 2013 and was restructured by an outside investor, it was China's flagship PV manufacturer for nearly a decade. Nicknamed the West Point of Chinese Solar PV industry, Suntech cultivated a large number of scientists and PV professionals who went on to have a large footprint in the PV industry. Spurred by Suntech's early success, the municipal government decided to develop Wuxi as a PV manufacturing hub. As of November 2014, Wuxi had 4.6 GW solar cell manufacturing capacity and 8.4 GW of module manufacturing capacity, accounts for approximately 10% and 20% of China's total capacity (Municipal Government of Wuxi, 2014). There were 45 PV manufacturing companies and suppliers located in Wuxi, among which 30 companies occupied niches in the main value chain, and 16 of them meet the competitive criteria outlined by the industry standards rolled out by MOIIT in 2013 (Municipal Government of Wuxi, 2014). Building on the infrastructure surrounding Suntech, a government-sponsored solar PV-specific industrial park broke ground in Wuxi in 2011, marking a clear policy intention to geographically consolidate the existing yet dispersed (in China's standard) solar PV manufacturing capacity in the city[59]. The industrial park brought 90% of the Wuxi's PV manufacturing capacity along with local PV suppliers in into the park, created a compact PV manufacturing ecosystem (Municipal Government of Wuxi, 2014). The industry park today does not only encompasses the entire traditional PV manufacturing value chain, the same government policy that created it also intended to attract more innovative organizations to the park by offering administrative incentives such as expedited permitting process. As of early 2015, a few PV cell and panel testing

[59] Interviewee #92

centers and research labs had moved into the industrial park. Similar solar-centric industrial parks can also be found in City of Changzhou[60], home of current world's largest solar PV producer, and in City of Suzhou near Canadian Solar[61].

Natural market forces and intentional industrial planning led to the growth of a dense solar PV manufacturing cluster in the YRD area. Figure 5.5 is a map showing top 10 ranked Chinese cell and module manufacturers and their global material and tooling providers in 9 key categories: flash-testing, Stringing machine, sliver paste, laminate machine, junction box, glass, ethylene vinyl acetate (EVA), etching machine, and back sheet. Noticeably, majority of the suppliers are located in China and a disproportionally large number of suppliers concentrate in the YRD area, with a few others locating along China's east coast in Guangdong, Hebei, and Liaoning Province. The rest are located in Western Europe and the U.S. The suppliers located in YRD area have close access to a large number of cell and module manufacturers. Figure D.1 to D.9 in Appendix D show the geographic distribution of global top suppliers in each category in 2013.

[60] Site visit #3
[61] Site visit #13

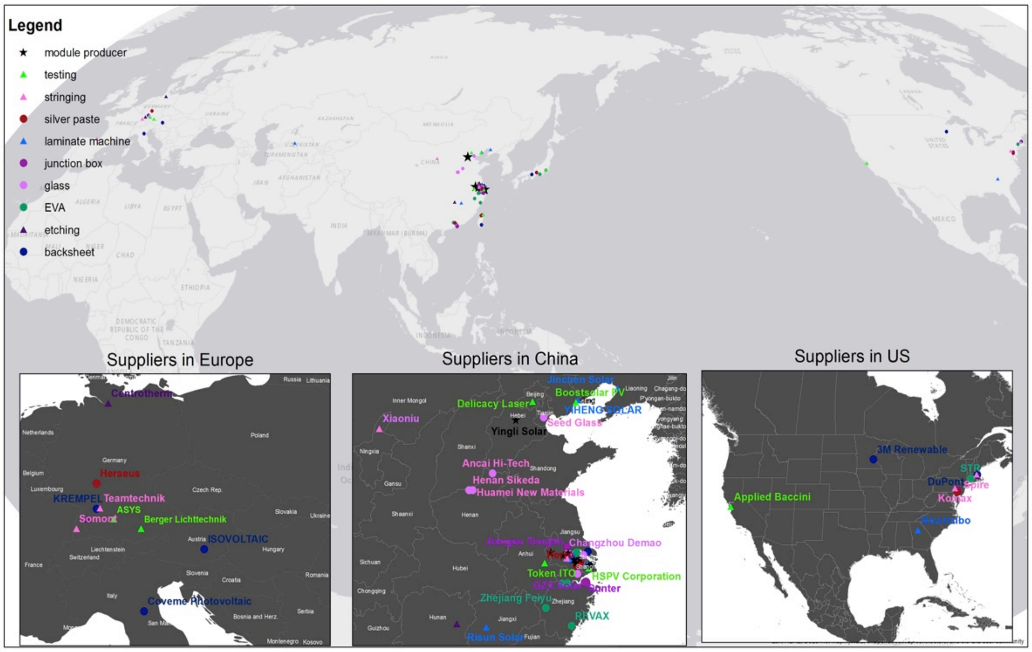

Figure 5.5 Top 10 Chinese PV Manufacturers and Their Suppliers

Data source: ENF 2013Top 10 Suppliers list.
Note: Map produced as part of the Stanford China Project by the author of this study, Jingfan Wang and Cait Pollock, all are members of the Stanford China Project team.

5.3.4. Strengths and Weakness of China's Solar PV Supply Chain

5.3.4.1. Strengths of the Supply Chain

In general, the supply chain in China is strong in producing bulk materials like wafer, aluminum frame, and panel accessories such as glass, junction box, connectors, cables as well as most of module manufacturing equipment. The processes to produce these components usually require labor and small to medium capital investment but not advanced knowledge and technological skills. Therefore, they fall into China's manufacturing comfort zone.

5.3.4.2. Weaknesses in the Ability to Manufacture Certain Supplies

However, China's supply chain is relatively weak in the following areas: silver paste, backsheet, and wafer and cell manufacturing equipment such as wire saw, automatic welding machine, automatic screen printing machines, Plasma-enhanced chemical vapor deposition (PECVD) machine, and flash testing and IV test (current-voltage) equipment. Chinese cell and module manufacturers who strive to produce high quality products often import these materials and equipment rather than buy from domestic suppliers.

The reason that China's supply chain lags in these areas has to do with its innovation capacity. Research has shown that an industry, a region, and even a nation's competitiveness depends on its innovation and its ability to combine innovation with production to generate competitive advantage (Bryson et al., 2015; Clark, 2013). Innovation is not a concept that exists only in labs. It permeates the entire manufacturing process and along the whole supply chain. The limitations faced by China's solar PV supply chain stem from its weak innovation capacity. For instance, to make an automated version of a welding and screen printing machine, it requires a combination of physics, electrical and mechanical engineering, and computer science knowledge. Flash testing machine requires a light source that imitates the natural sunlight, and to produce the artificial sunlight, advanced optical physics knowledge and high precision manufacturing capability are needed. I-V test equipment requires physics and electrical engineering knowledge as well as high precision manufacturing capacity. As for silver paste, the ideal product should be able to be applied thin and tall at the same time in order to reduce the surface area on a solar panel it covers while at the same time increase its electric conductivity. Lots of chemistry and chemical engineering work goes into creating those two properties. Similarly, chemistry, chemical engineering, and physics knowledge are necessary to produce good back sheet that can sustain long hours of ultraviolet radiation and chemical erosions. China's weak foundation in basic science and advanced engineering research makes it difficult for its solar supply chain to develop strength in areas that requires advanced scientific and technological knowledge.

Blocking mechanism 5.1: Weak science and engineering foundation made it difficult for the Chinese solar supply chain to develop strength in areas that requires advance knowledge and manufacturing skills.

Nevertheless, as China makes inroads in solar PV science and technology innovation (documented in Chapter 3), its solar PV supply chain also evolves. In recent years, a number of Chinese companies have mastered the technologies and know-hows in a few areas. For example: wire saws produced by the Zhejiang-based Jinggong Science and Technology are now widely used by Chinese wafer producers. Changzhou SVECK Photovoltaic New Materials emerged as a competitor in EVA area. The 48th Research Institute has strong capacity in manufacturing diffusion furnaces. Despite the improvement, there are still bottleneck issues waiting to be broken, the prominent among which are silver paste, automatic welding machine, and flash test equipment[62].

Figure 5.6 illustrates the relative strengths and weaknesses of the solar PV supply chain in China and how they progress over time.

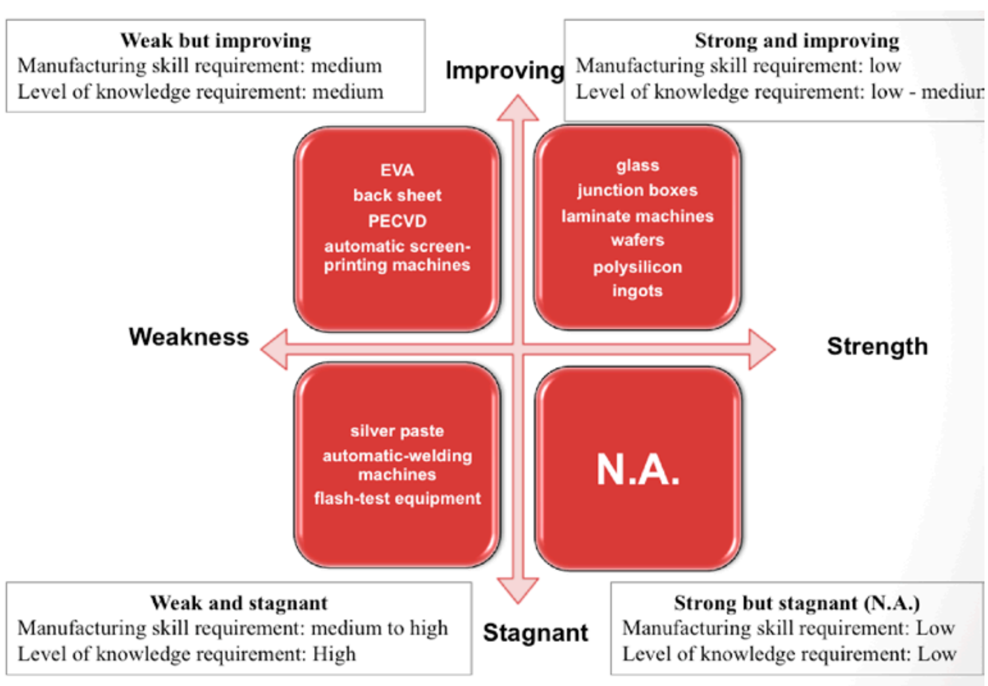

Figure 5.6 Strengths and Weakness of China's Solar PV Supply Chain

[62] Based on interviews with interviewee #46, #71, #88, #97, #99, #102, #104

5.3.4.3. Weakness in Supply Quality

5.3.4.3.1. Observing the quality gap between Chinese and Western supplies

Weakness of the supply chain can manifest in multiple ways and the lack of manufacturing capacity is only one of them. When one supply chain link is considered weak, it does not necessarily mean that there is a vacuum of domestic suppliers. In fact, as Table 5.2 demonstrates, even in areas that are considered as stagnantly weak such as silver paste, flash testing, and automatic welding, there are numbers of active Chinese suppliers, indicating some capacity to produce those components. However, the key difference here is the quality. For example, silver paste produced by Chinese suppliers does not demonstrate as good conductivity as products made by overseas producers like DuPont. In cases like automatic welding machine and flash test equipment, the precision of Chinese-made equipment is lower than popular German brands. Lower-quality Chinese products in these areas may exist to satisfy lower tier Chinese cell and module producers because they are cheap, but for the top tier Chinese producers, they would not risk the quality of their final products by choosing domestic brands in areas where the supply chain has not proven its strength yet[63].

The quality gap between Chinese and foreign supplies is more pronounced in the cell manufacturing stage than the module stage. During the visits to seven PV manufacturing facilities located in China[64], it is noticeable that almost all equipment used in solar module assembly is provided by Chinese suppliers. However, the percentage is much lower among solar cell manufacturers. Chinese PV manufacturers have revealed strong confidence in the precision and quality of Chinese-made module-manufacturing machinery but low confidence in that of Chinese-made cell-manufacturing machinery.

[63] Interviewee #57, #69
[64] Site visits #3, #10, #12, #22, #24, #26

As the R&D director of Canadian Solar[65] once said, "Although all equipment experience downtime, it happens to Chinese equipment more often than it is to German equipment." If one piece of equipment breaks down, it will halt the production of the entire cell production line. The productivity will suffer as a result. However, the worry for equipment reliability is a lesser problem to Chinese cell manufacturers compared to the concern for cell efficiency loss.

5.3.4.3.2. Quality gap explained

Interviews with executives of Chinese companies revealed that the average efficiency of solar cells produced using all made-in-China materials and equipment is marginally lower compared to cells made using all western-made supplies. Part of the reason is highlighted in the silver paste example: lower quality parts lead to lower quality final products. But an even more important reason has to do with tooling stability. Stability refers to the ability of the production line to *consistently* produce high quality products. The director of the 48th Research Institute breaks down the significance of tooling stability in the following way. Imagine two production lines, Line A and Line B. They are both designed to produce 19%-efficient solar cells except that Line A has higher stability than Line B. As a result, even though the best cells produced by both lines are the same, i.e. 19%, Line A is able to produce 19%-efficient solar cells 90% of the time whereas Line B is only able to do so 80% of time. Simply put, 90% of the products produced by Line A are at 19% efficiency (with acceptable deviation, a.k.a $\pm 3\sigma$), but only 80% of the products made by Line B are of that caliber. Figure 5.7 demonstrates the distributions of the two production lines.

[65] Interviewee #101

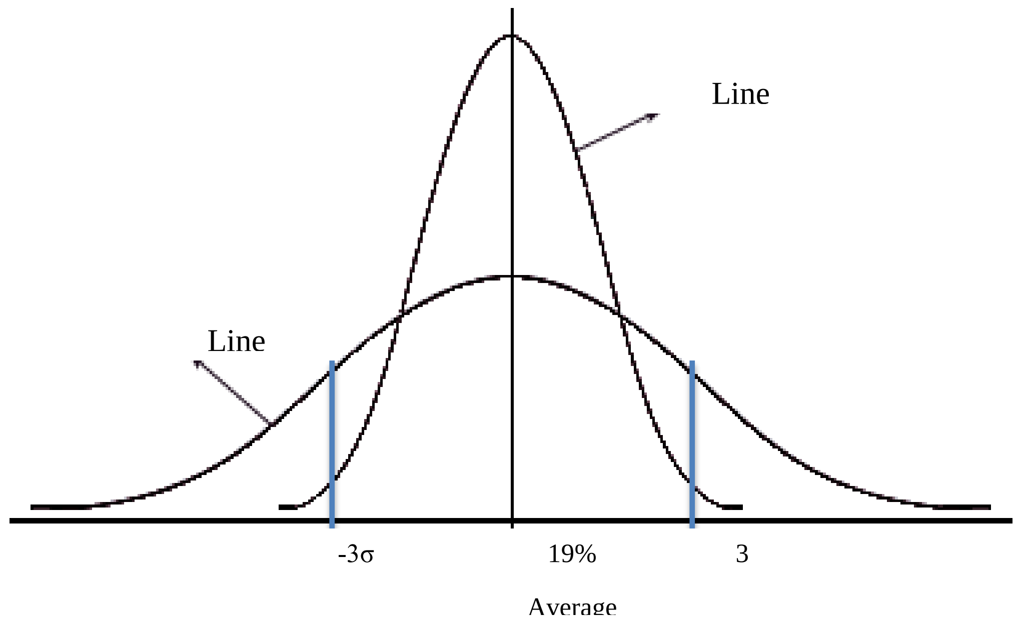

Figure 5.7 Product Quality Distributions of Two Production Lines with the Same Average Efficiency

As shown in Figure 5.7 the average efficiency of all the products produced by Line A is higher than that of Line B. If a company plans to sell only the 19%-efficient solar cells, not lower, it will incur 10% (90% minus 80%) more loss if they use Line B compared to using Line A. In reality, China made tooling is like Line B, whereas leading foreign tooling is like Line A[66]. As important as reliability is, equipment breakdowns are one-off events, they do not happen every day. Yet, stability is a systemic factor that has persistent effect on the performance of a production line and its final products. Chinese made equipment is often subject to such shortcomings. Even though they may come with a lower price tag, as today's Chinese solar cell manufacturers pay increasing attention to the performance of their product, many of them prioritize tooling quality over price. One can have a vivid sense of the dominance of imported cell-manufacturing equipment by taking a walk in production facilities of top tier Chinese solar cell producers.

5.3.4.3.3. Causes of the quality gap

[66] Interviewee #104

Chinese tooling is not as strong as its foreign competitors in reliability and stability, and once again, weak science, technology and engineering foundation are the underlying cause of the problem.

First, parts made by Chinese are of lower quality than the parts made by the west. Just like China is not particularly strong in make key components of solar cells such as silver paste, it is also weak in making key parts for cell manufacturing equipment such as shafts, motors, etc. Second, when it comes to equipment design, China also lags behind. It all boils down to less rigorous science training and the lack of deep understanding of the fundamental science and engineering theories behind equipment design[67].

As a result of the above-mentioned factors, Chinese solar cell companies, for a long time, relied primarily on imported equipment for key cell-production processes such as diffusion, etching, stringing, screen printing, and flash testing. Module production is different. Because it is mostly a process of assembling parts together, it has a much lower requirement for precision and efficiency, so most Chinese producers use domestic equipment.

5.3.4.3.4. Closing the gap

Recent trends suggest that Chinese-made tooling has made progress over time, and many Chinese PV manufacturers have shown their interest in shifting from importing equipment to using domestic equipment. An analysis using ENF’s 2013 Chinese PV Industry Survey data shows that Chinese tooling companies made inroads in a few cell producing equipment areas. As shown in Table 5.4, only two types of equipment, screen printer and firing furnace, completely rely on imports. For other cell-manufacturing equipment, i.e. cleaning, diffusion, PECVD, etching machines, and cell tester and sorter, a majority of the Tier 1 companies used either 100% domestically made equipment or a mix of Chinese and foreign equipment.

[67] Interviewee #53, #104

Innovative SMEs are instrumental in the uptake of Chinese-made solar cell manufacturing equipment. Using the same ENF data, this study pinpoints a number of rising Chinese equipment suppliers. Beijing-based Sevenstar Electronics, Wuxi-based Rusitec Science & Technology, Shenzhen-based Exact S.C, and Taiyuan-based The Second Research Institute of China Electronics Technology Group Corp are active suppliers of cleaning machines. The 48th Research Institute of China Electronics Technology Group Corp is the main domestic diffusion furnace and etching equipment supplier. In the cell tester/sorter category, Chinese equipment manufacturers also made progress. Four out of the six Tier 1 Chinese cell manufacturers used either all-Chinese equipment or a mix of Chinese and foreign equipment. Xi'an-based GSolar and Shanghai-based HSPV Corporation are the major cell tester and sorter suppliers. Screen printer and firing furnace remained dominated by Western equipment suppliers by 2013. However, recent interviews[68] and factory[69] visits conducted by the author in the second half of 2014 and first half of 2015 showed that the 48th Research Institute had successfully penetrated the firing furnace market by sealing a deal with one of the top tier Chinese cell producers.

Table 5.4 Source of Solar Cell Manufacturing Equipment of Tier 1 Chinese PV Producers in 2013

Company/Process	Trina	Yingli	Suntech	JA Solar	Renesola	Hanwha
Cleaning	China	China	Foreign	China	Mixed	China
Diffusion Furnace	Foreign	N.A.	China	China	Mixed	China
Etching	N.A.	Foreign	Mixed	Mixed	Mixed	Mixed
PECVD	N.A.	Foreign	Foreign	Foreign	Mixed	Foreign
Screen Printer	Foreign	Foreign	Foreign	Foreign	Foreign	Foreign
Firing Furnace	N.A.	N.A.	Foreign	Foreign	Foreign	Foreign
Cell Tester/Sorter	China	China	China	Mixed	Foreign	Foreign

Source: ENF Chinese Cell and Panel Manufacturers Survey Continuous Edition, 2013.
Note:
Data on Jinko and Canadian Solar are not available.
The subscription to the ENF database came through the Stanford China Project.

[68] Interviewee #14, #59, #63, #65 #89, #103, #104
[69] Site visit #24, #26

The rising level of domestically made solar cell manufacturing equipment reflects the improving quality of Chinese machinery, and it has a significant impact on production cost. The next section will explore the relationship in details.

5.4. Advantages with A Robust Domestic Supply Chain

5.4.1. Driving mechanism 5.2: Domestic supply chain provides Chinese PV manufacturers with cheaper alternative tooling and material options, which directly reduces the production cost.

Interviews conducted by this study show that for the same piece of manufacturing equipment, Chinese suppliers on average sell for only 1/3 to half of the price asked by western suppliers[70]. For instance, during the rapid industry expansion period, the 48th Research Institute conducted over 100 Engineering, Procurement and Construction (EPC) projects to install 25MW PV production line for Chinese producers, most of which were SMEs. Using 100% self-design and self-produced equipment, the 48th Institute was able to complete a project for about ¥ 60 million, or a little less than $10 million, whereas it costed about ¥100 million (approximately $16 million) to buy a similar production line from overseas suppliers[71]. Another example from Hangzhou-based thin film solar cell producer Advanced Solar Power (ASP) depicts a scenario of how in-house tooling design and manufacturing can save PV producers a great deal of money. ASP's self-designed and domestically manufactured automatic scribing machine costs only 1/10 of imported equipment of the same kind. Admittedly, there is a quality difference between equipment made in China and those made in the West, the sizable saving with domestically produced equipment gives Chinese PV manufacturers a significant cost advantage over their foreign competitors who pay the cost premiums for Western made equipment.

[70] Interviewee #97, #103, #104,
[71] Interviewee 104

5.4.2. Driving mechanism 5.3: Cheaper, domestically produced tooling and materials gave Chinese PV manufacturers bargaining power in negotiating with foreign suppliers, which indirectly reduce their production cost.

Even in areas where quality is a greater concern than cost, Chinese PV manufacturers were able to achieve a good amount of cost reduction by threating to switch to domestic suppliers when negotiate with their foreign suppliers. They can leverage the fact that there exist Chinese domestic materials and tooling suppliers who can satisfy their demand by using domestically produced materials and tooling as their bargaining chips, Chinese PV manufacturers can negotiate for a lower price even if they still ended up buying from foreign suppliers. An anecdote from the 48th Research Institute suggests that after it mastered the techniques to produce good quality wire saw (a machine used in slicing ingot into thin wafer layers), It priced the equipment at ¥1.5million (approximately $250,000). It forced the incumbent western wire saw producers to reduce their price from ¥ 5million (approximately $800,000) to ¥ 2.5million (approximately $400,000) in order to retain the Chinese customers. From Chinese PV manufacturers' perspective, they could either save ¥3.5 million (70%) by switching from foreign equipment to Chinese equipment or save ¥ 2.5 million (50%) by staying with the same foreign supplier but using the 48th Research Institute as their bargaining chip. It is ultimately up to the PV manufacturers to decide which one they value more, cost saving or equipment quality, but in either case, the presence of domestic equipment suppliers gives them a significant cost advantage.

The quote from the deputy director of the 48th Research Institute captures the gist of domestic chain's contribution to the cost competitiveness of the Chinese solar PV industry.

"The ability to produce tooling domestically is the most important reason why solar panels made in China are so much cheaper than everywhere else."

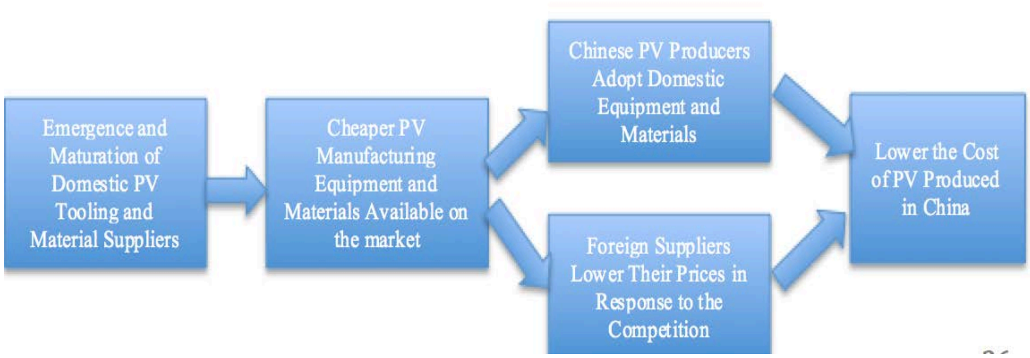

Figure 5.8. Two Pathways of Cost Reduction with Domestic Suppliers

5.4.3. Driving mechanism 5.4: Chinese suppliers disrupted the industry status quo and unleashed significant cost reduction potentials for Chinese and foreign PV producers alike.

Besides the improvement in domestic tooling supply, the maturation of PV material supply chain, especially the emergence of a few large silicon and wafer suppliers, has also contributed to cost reduction. In 2005, only 10% of China's polysilicon demand was met domestically. Since then, a number of silicon producers like GCL Poly, TBEA, Daqo New Energy, China Silicon Corporate, etc emerged in China and grew quickly in terms of production capacity and product offerings. As a result, domestically produced poly-silicon met 50% and 60% of the totally demand in China in 2010 and 2014, respectively (CCID, 2015a; NDRC, 2011).

Wafer supply chain is even stronger in China. Started at a miniscule scale in the early 2000s, within 10 years, the wafer supply chain in China has developed so much that by 2014 it is not only self-sufficient, it produced over 38 GW, which accounted for 76% of the global wafer production, and exported 9.27 GW. The fast capacity expansion in silicon and wafer industry in China triggered a rapid price decline, which brought a disruptive change to the PV industry. Interviews with polysilicon executives revealed that polysilicon production cost followed a steep downward trajectory[72]. Global commodity polysilicon was traded at around $200 in the late 2000s. (Bloomberg Finance L.P., 2014a). However, cost decline started as companies like GCL Poly grew. Between 2010 and 2014, the cost of polysilcon made by leading Chinese producers declined by 80%, from $60 (2010) → $20 (2011) → $18 (2012) → $16 (2013) → $12 (2014). During the same time, prices at a major Germany polysilicon producer declined only 20%. Note that polysilicon and wafer together account for over 40% of the final PV module cost (BNEF, 2014b), the low cost products provided by Chinese suppliers in these two categories have unleashed great cost reduction potentials for Chinese and foreign PV manufacturers alike. With additional saving on transportation cost, Chinese companies benefits more from the thriving domestic polysilicon and wafer suppliers.

5.4.4. Driving mechanism 5.5: Domestic supply chain locks the cost and logistic advantages in China.

The advantage with domestic Chinese supply chain also manifests in Chinese companies' decision to expand their business overseas. Since 2013, many Tier 1 Chinese PV manufacturers started to build overseas factories, mainly for the purpose of circumventing the import duties imposed by the U.S. Interviews with two companies that have built cell production facilities in Southeast Asian countries showed that although labor cost is cheaper in those countries, the overall production cost is 10% higher due to the weak local supply chain.[73] Local suppliers can meet the demand for low-key components such as screen, aluminum paste, etc, but Chinese companies' overseas facilities still have to import key components like wafer and sometimes even equipment such as diffusion furnace from China, in addition to the materials and equipment that they usually purchase from foreign suppliers, things like silver paste, stringing machine, etc.

[72] Interviewee #57, #63
[73] Interviewee ID #53, #96

The higher costs associated with wafer and equipment importation offset the lower labor cost offered by those Southeast Asian countries. If it were not for the tariff circumvention purpose, Chinese companies cannot justify the decision to open an overseas cell production facility based on the economics[74]. In other word, the cost advantage as a result of domestic supply chain is difficult to duplicate outside of China. Even for Chinese PV manufacturers, their greatest cost advantage comes from operating inside China with their domestic suppliers.

5.4.5. Driving mechanism 5.6: Domestic supply chain enables Chinese PV manufacturers to be agile and flexible.

In the earlier example about ASP, their self-designed equipment does not only reduces production cost, but also optimizes its production efficiency because the equipment was tailored to meet the specific demand of its own production lines. This highlights another key mechanism through which having a domestic supply chain is advantageous, that is it is flexible and agile (Chan & Chan, 2010; Fohrholz & Gronau, 2011) (See Chapter 4 Section 4.3.2.1). The flexibility and agility stem from spatial proximity and localized learning.

Research has found that the creation and diffusion of knowledge, especially tacit knowledge, is difficult to transfer across large geographical space. Face-to-face interaction and local learning are more suitable forms (Bathelt, Malmberg, & Maskell, 2004; Malmberg & Maskell, 2006). In the ASP case, all but one encapsulation equipment are self-designed and made in China. The ability to do so allows ASP to easily manipulate their equipment to meet the requirement of new products. For instance, ASP used to use parallel circuits in their early products, but when new product that requires series circuits was set for production, ASP was able to modify its equipment to accommodate the new product design. Interviews with ASP chairman indicated that this

[74] Interviewee ID #96

would not be possible if they were to use imported equipment. The communication barriers with foreign designers and manufacturers, which include issues with language, time difference, geographic distance, are very high. Therefore, it would take a much longer period and require more manpower from ASP to tweak the production line with foreign suppliers. In contrast, the self-designed, domestically produced equipment allowed ASP the agility in bringing new product to market. They can easily and quickly modify their production line and speed up the "technology to market" cycle.

In addition to being agile, the presence of a domestic supply chain also makes the Chinese PV manufacturers more flexible in their production process. It is often the case that large PV manufacturers co-design equipment with their tooling suppliers. PV producers would self-design a few key pieces of equipment and then send the design blueprints to tooling suppliers of their choice. When working with domestic tooling suppliers, Chinese PV manufacturers can either send their design technicians to the suppliers or invite the suppliers' technicians to come to them. The idea is to have both the equipment buyer and producer work together under the same roof at every major step of the equipment design and production process in order to make sure the functions demanded by the former are truly incorporated into the equipment. This joint-development process is not a one-shot effort. Instead, it involves a lot of experimenting, trail-and-error, fine-tuning and troubleshooting, which are all made easy when both parties are in the same geographical space. By working closely with domestic tooling suppliers throughout the design and production process, Chinese PV manufacturers can also internalize the knowledge associated with the equipment and be confident in operating, and more importantly, experimenting with the equipment and be able tweak them when needed.

An example from a factory tour of a medium size solar cell producer based in Changsha best highlights this point.

The cell manufacturer is an original equipment manufacturer (OEM) of multiple large Chinese PV producers. The exact product they produce depends on the orders they receive from their customers. Unless the factory runs on full capacity, only two or three out of the four firing furnaces are in active mode. Among the four firing furnaces, three of them are jointly developed by this very OEM and the 48th Research Institute; the fourth one is a German brand. The operating order in this factory is that it would max out the capacity of the domestically made fire furnaces before they turn on the German furnace. The reason given by the factory manager is that workers find it is easy to experiment new things with the Chinese equipment. They can modify the furnaces by changing or adding parts to give the furnaces new functions. As a result, the furnaces became more versatile than they originally intended to be, which in turn allowed a lot more flexibility in production. Flexibility is essential to OEMs like this factory, as they often need to adjust their production process to meet specific demands from their buyers.

In contrast, the German furnace, albeit from a world top supplier, does not adjust to new production conditions easily. The complaints about the German equipment were not about the quality of the furnace itself but about its ability to fit into the particular demand of this production line. First of all, the equipment manual and control panels are all in English; few production line workers have the language capability to operate the equipment. Even if a few have learned the basics in order to run the machine, the chances that they can experiment with it and make it versatile are close to zero. In addition, technicians who work on the machine also express cultural shocks in some basic aspects such as the use of symbols and colors, and the arrangement of the buttons on the control panels. For example, Chinese workers are used to seeing green signal lights as an indication of the machine is in operation. However, the German furnace uses a red light for the same purpose. It came across as counter-intuitive to Chinese workers. Small things like that confused Chinese workers and make them declare that the German furnace is difficult to use.

This example with the OEM factory contextualizes how a domestic tooling supply chain can enable PV manufacturers to be agile and flexible. The reasons can be boiled down to two points. First, the geographic proximity allows PV manufacturers and their suppliers to collaborate closely on equipment design and manufacturing. It gives the PV manufacturers first-hand information about the equipment and opens up the possibility of customized modification. Second, the communication barrier is low between parties from the same country, whereas the differences in language, custom, and working cultural between parties from different countries, no matter how trivial they are, prevent information from flowing freely and hurt the manufacturing performance.

5.4.6. Driving mechanism 5.7: Domestic supply chain improves Chinese PV manufacturers' productivity, indirectly reducing production costs.

Domestic suppliers' contributions to the low PV production cost in China are not limited to providing cheaper tooling and materials. They also enabled productivity improvements in Chinese factories through the following two means.

First, the ability to produce equipment, materials and parts domestically opens a door to all kinds of process innovation that can increase productivity. In the innovation chapter, we gave an example from Jinko's solar cell production line. An additional mechanical arm, made by a local machinery manufacturer, was added to a cell testing machine to ensure that in situations where the cell transportation belt is halted, this additional mechanical arm can still bring cells from elsewhere to keep the testing machine occupied. If it were not for the additional mechanical arm, the testing machine would have to be paused completely when the transportation belt ceases to work. With the additional arm, the downtime is avoided or at least reduced and the productivity of the production line is higher than it would otherwise be. Although the mechanical arm may marginally increase the total investment cost of that production line, over the long run, the higher productivity can lower the average production cost of the line. Similarly, the examples about ASP and the OEM from previous section also give illustrate domestic supply chain's enabling role for productivity-enhancing process innovations.

Secondly, domestically made equipment is easier and cheaper to maintain. If a Chinese-made equipment breaks down in a Chinese factory, the repair time is shorter compared to that of imported equipment because of the geographic proximity between domestic suppliers and the PV manufacturers. During a visit to Sunergy's PERC production facility, the production line was on pause because the atomic laser deposition machine made by a Danish company had been broken for three weeks at that point[75]. It was not clear to the R&D director when Danish engineers would arrive to fix the problem, but one thing was clear: until the Danish repair the equipment, the entire PERC cell production at this facility would remain on hold. Given the fact that PERC cell is Sunergy's flagship product, the frustration was obvious among its employees. This example demonstrates the downside of relying on foreign equipment and material supplies. The long wait time for repair and troubleshooting hurts productivity, which unavoidably leads to lower output and eventually loss in revenue for the firm. Furthermore, given the same fixed cost, lower output means higher average production cost. It jeopardizes the firm's competitiveness in the market.

5.5. A Case Study of the 48th Research Institute

By far, this study has explored the development path of the solar PV industry in China, its current characteristics, its strengths and weaknesses as well as its contribution to the competitiveness of the industry. The interaction between firms' strategies in response to changing market conditions and the government's industrial and innovation policies are two major driving forces of the supply chain development.

This section use a case study of the 48th Research Institute, one of the most successful Chinese solar PV manufacturing equipment suppliers, as an example to

[75] Site visit ID #26

illustrate how innovation at the firm level enables the growth of the supply chain, which in turn lends competiveness to the PV manufacturing industry.

5.5.1. History of the 48th Research Institute

One cannot avoid talking about the 48th Research Institute when studying the development of China's domestic tooling supply chain. Its name came up again and again in the author's conversations with professionals from the industry in China. Officially named the Forty-eighth Research Institute of China Electronics Technology Group Corporation (CETC), the 48th Research Institute is one of the 58 research institutes affiliated with China Electronics Technology Group Corporation, a state-owned large conglomerate with a tie to the defense industry.

Back in its defense lab age, the 48th Research Institute specialized in areas including thermal engineering, electronic engineering, and semiconductor devices. When the solar PV industry began to emerge in the early 2000s, the 48th Institute found it had just the right skillset for the industry: solar cell is essentially a semiconductor device that turns photons into electrons, and the production of solar cells requires a suite of thermal devices such as diffusion furnace and firing furnace, as well as electronic equipment like the plasma-enhanced chemical vapor deposition (PECVD) equipment. Convinced that the solar industry was going to gain traction, the 48th Institute began to design equipment that can be used for PV production. By 2002, orders from domestic solar cell producers for diffusion furnace, etching machine, and fire furnace started to come to the institute. By 2004, PECVD equipment produced by the instituted was used in Chinese solar cell production lines, including the ones at Suntech. In 2005, the 48th Institute rolled out the second-generation diffusion furnace, firing furnace, plasma etching machine and PECVD equipment, followed by the release of the third generation products in 2006. While the Institute mastered equipment design and production for solar cell manufacturing, it also made progress in the silicon realm. In 2007, it self-designed and produced equipment used in mono-silicon production and ingot casting. To further strengthen its capacity as a solar PV tooling supplier, the 48th Institute debuted its turnkey solar panel production system in 2008, which automate the entire panel production process including silicon growing, ingot casting, wafer slicing, solar cell production, and module encapsulation[76].

With this newly gained capacity to provide turnkey systems, the Institute began to see an increasing number of orders from Chinese PV manufacturers. The rapid manufacturing capacity expansion fueled by generous overseas Feed-in Tariffs in the mid- to late-2000s created an unprecedented demand for equipment made by the 48th Institute. Since 2006, it has built over 100 25MW level solar cell or panel production lines, mostly for SMEs in China.

The global financial crisis in 2008 turned out to be not as much a challenge as an opportunity for the Institute. The stimulus package in the U.S., E.U. and China all made the clean energy industry a priority area for government stimulus fund, which further energized the solar deployment market and created an even bigger market for Chinese PV producers and tooling suppliers like the 48th Institute. As a tooling supplier to the Chinese PV manufacturing industry Institute, the Institute shares the same pulse with the industry. So when the trade dispute with E.U. and the U.S. hit the industry hard, they also made it challenging for the 48th Institute. Nevertheless, as surviving Chinese PV manufacturers turned to innovation for their next source of competitiveness and began to produce higher-efficient products, the 48th Institute anticipates renewed opportunities to make new equipment that can be used to produce high efficiency solar cells like PERC, HIT, etc.

5.5.2. The 48th Research Institute's Impact on the Localization of Tooling Supply

5.5.2.1. Achieve Self-sufficiency in PV Manufacturing Equipment Production

[76] 48th Research Institute: http://www.cs48.com/html/48s/fzlc/

The importance of the 48th Institute's ability to make turnkey systems with a complete set of silicon, solar cell and module manufacturing equipment cannot be overstated. It marks the achievement of the 100% localization of tooling production. As discussed in the previous section, a whole suite of benefits comes with using domestically produced equipment. They are cheaper, easier to use, adaptive to new production requirements, can be repaired relatively quickly.

The 48th Institute's motivation to develop the ability to produce the entire set of PV manufacturing equipment stems from both market opportunity and its tie to the central government.

The booming PV manufacturing market and the rapid capacity expansion associated with it created a large demand for equipment made by the 48th Institute (***market creation***). It seized the market opportunity and developed the ability to supply tooling needed for the domestic industry (***knowledge development and diffusion***).

Nevertheless, the 48th Institute could have chosen to play within its strong suit and become the suppliers of a selection of the production equipment. It is arguably a more economically efficient decision. But it was not the path that the Institute pursued. The decision to become a one-stop PV tooling supplier was driven by the 48th Institute's role as a State-owned Enterprise (SOE). Literatures often depict SOEs as bureaucratic, less efficient, slow in response to market trends, and prone to government influence (Ding, Zhang, & Zhang, 2007; Li et al., 2006; Montinola, Qian, Weingast, & Introduction, 1996). The case with the 48th Institute shed some new light on the theory.

It is true that SOEs are prone to government influence, but it is not necessarily a bad thing. In the 48th Institute's case, government policy ***influenced its direction of search*** and led to a leap forward in mastering PV tooling manufacturing capabilities.

When the Chinese government sent clear and strong signals in its 11th and 12th FYP about developing the solar industry, the Institute saw both a market opportunity and a social responsibility as an SOE to improve the domestic PV tooling manufacturing capacity. The 11th FYP for Renewable Energy Development, the 12th FYP Special Plan for Solar Electricity Generation Technology Development, and the 12th FYP Special Plan for Solar PV Industry Development all listed the equipment manufacturing as a key area of development. The typical mindset of an SOE is to do "what the economy needs", and since the FYPs clearly pointed out that the need is to become more capable of making PV tooling domestically, the 48th Institute naturally took on the task as its calling. It did not make the most economically rational calculation in deciding what equipment choice would yield the highest economic return. Rather, it decided that the social mission, which was to make the PV industry in China self-sufficient of PV tooling supply, is more important. In an interview with the deputy director of the Institute, he stated,

" The commanding goal of the Institute is to conduct tooling-related R&D for the entire solar PV value chain in China. This is a responsibility we have as an SOE. "

They see the role they play in producing tooling for the entire Chinese PV manufacturing industry, without leaving a single gap, as their social responsibility. By fulfilling the responsibility, they do their share to contribute to the greater economic development of the nation. To an SOE, its social responsibility often trumps economic calculations.

In order to best fulfill its social mission, the 48th Institute decided to become fully integrated so that they can be the first user and experimenter of their own equipment (***influence on direction of search***). Starting from 2011, the Institute became a solar cell producer, fully equipped with tooling produced in-house so that they can collect first-hand information about their own equipment and conduct trial-and-error to improve their performance. By the second quarter of 2015, they had a cell manufacturing capacity of 500MW. It also produces wafer and ingot and assembles PV modules. The in-house commercial production capacity allows timely feedback on equipment performance between producer and user, which are the same party in this case.

It is clear that the policy signal to develop domestic PV supply chain and the tie between the 48th Institute and Chinese government influenced its research agenda and business decision. A private company with the same technical credential is unlikely to make the same decision to become a one-stop tooling supplier because it is technically demanding and economically suboptimal. Nevertheless, the 48th Institute's social mission influences its firm strategy and leads it to consider beyond its *institute-level* economic wellbeing and optimize from the *industry's* perspective.

5.5.2.2. Enhance the Penetration of Domestically Produced PV Manufacturing Equipment through Quality Improvement

For a long time, Tier 1 Chinese PV producers preferred Western equipment because of the high quality they offer. Even though domestic tooling suppliers can be used as a bargaining chip in price negotiation, the benefit of agility, flexibility and short repair wait time cannot be realized without actually using domestic tooling. In other word, unless the quality of Chinese made equipment improves, Chinese PV producers are not able to take the full advantage of the domestic tooling supply chain. The interview with the deputy director of the 48th Institute revealed an interesting history between the Institute and large Chinese Tier 1 PV producers that were there from the inception of the industry. Before these companies became world famous, many of them bought equipment from the 48th Institute. However, after they became publicly listed companies and went on to receive large orders from overseas customers, companies stopped using Chinese equipment and turned to foreign suppliers for better equipment instead. Losing customers made the 48th institute motivated to improve the performance of their own products.

Better equipment design, expanded equipment capacity, and higher degree of automation are three major ways to improve equipment performance. Equipment performance is predicated on its design. Design is the soul of a machine. The actual equipment is nothing more than the design being materialized. Issues with stability and reliability (Section 5.3.4.3.2) mostly stem from design imperfections. They can be improved upon with incremental fixes to the existing design or with a new design. The former is done usually in an experimental way through trial-and-errors. The fact that the 48th Institute has in-house production line fully equipped with its self-designed equipment allows them to experiment with incremental improvements. When incremental improvements can no longer deliver the desired quality, new technological pathways, i.e. hardcore innovations, are needed. The 48th Institute is arguably in the best position to innovate because of its history as a public research institute. By default, its primary mission is to innovation. In fact, it has developed a track record of coming up with equipment with new designs. Take diffusion furnace for an example, over the course of five years, four types of diffusion furnace were designed and produced in order to meet the evolving production requirement by the PV manufacturers (***knowledge development***).

In addition to newer designs, the 48th Institute also produces bigger-size equipment in order to satisfy the capacity expansion in China. As the overall capacity increases, the size of a single production line also becomes bigger and bigger to keep up with the ever growth PV manufacturing capacity in China. A typical capacity of one production line in 2013 was 25 MW, but in 2015, large production facility prefers 30 to 35MW. Bigger production line capacity requires larger parts such as solid shafts. The 48th Institute spent 2 years in R&D and eventually mastered the method to produce and integrate larger solid shafts to existing equipment in order to deliver greater power. This timely development made its equipment popular among Chinese buyers who seek greater production capacity.

Last but not least, the 48th Institute also took equipment automation seriously. Acknowledging the fact that the PV manufacturing processes are becoming increasing automated, Chinese PV producers ramped up their deployment of automated machines every time they build a new facility (see Section 4.3.1.1 in Chapter 4 for an example of production automation in China). Automation is a weakness of Chinese tooling manufacturers comparing to historical heavy machinery manufacturing powerhouses like Germany. Realizing that equipment automation is an unavoidable future, the 48th Institute prioritized the R&D of automated machines, most noticeably automated diffusion furnace, automated etching equipment, automated PECVD, etc., in their research agenda. According to its manufacturing manager[77], a 25MW cell production line with 100% the latest 48th Institute-designed equipment requires 60 people to operate, that is down from 150 people required by its first generation production line and 120 people required by the second generation production line. This labor requirement is still higher than the best-automated production line made by western supplier, but stand-alone automated equipment such as diffusion furnace, etching and PECVD equipment have started to be adopted by Chinese PV producers.

In summary, building on its historical research capacity in thermal engineering, electronic engineering, and semiconductor devices, the 48th Institute expanded its product family of diffusion and firing furnace, etching machine, and PECVD equipment with newer versions that have more functions and greater power. This effort paid off. Tier 1 Chinese companies started to use equipment provided by the 48th Institute since 2010, and by 2013 half of the Chinese Tier 1 companies use diffusion and etching equipment made by it and at least 1 company uses PECVD equipment made by the Institute. [78]Associated with the adoption of domestically made tooling was reductions in PV production cost.

5.5.2.3. Sprout *Knowledge Diffusion* and Expansion of the PV Tooling Industry

As the first mover in the PV equipment manufacturing area, the 48th Institute does not only become a leading domestic supplier, it has also spun off a number of domestic tooling suppliers. In the process of developing tooling design and production knowledge,

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[77] Interviewee #103

[78] Data source: ENF Chinese Cell and Panel Manufacturers Survey Continuous Edition, 2013. Analysis results are summarized and turned into Table 5.4.

the Institute fostered a large number of R&D experts and skilled workers along the way, many of them later became entrepreneurs and started their own business in the tooling production realm. For example, Exact S.C., a leading Chinese PECVD equipment and diffusion furnace provider is founded by a group of the former 48th Institute employees. Shenzhen Fullshare Equipment (former Han's PV), headed by a former deputy director of the 48th Institute, is now a serious contender in the diffusion furnace and PECVD field. Qingdao-based Wuzhuan Equipment has also made inroad to the firing and diffusion furnace market after a former 48th Institute senior researcher came on board.

Companies spun off from the 48th Institutes increased the number of players in the equipment production segment of the solar PV industry in China. They ***created positive externalities*** by introducing market competition to the incumbent players, including the 48th Institute. Like what market competition always do, they expanded product diversity, increased product quality, further lowered the price, and pushed for all parties to innovate and offer newer and better products.

To summarize, the example of the 48th Research Institute provides vivid examples about how firm level innovation drives the development and maturation of the solar PV supply chain development in China and enables Chinese PV manufacturers to upgrade their products and production processes in order to stay competitive in the market.

5.6. Summary and Policy Implications

Chapter 4 of this dissertation found that a robust and regionally clustered supply chain is a unique feature of the solar PV industry in China. This chapter studies the history of the solar PV supply chain and its role in building the competitive strength of its domestic PV manufacturing industry. It is discovered that the supply chain in China is complete, robust, and geographically concentrated. Its inception was due to market opportunity, but its growth was facilitated by both market force and government policy and planning. Rapid PV manufacturing capacity expansion in response to foreign demand in the mid- to late-2000s gave the supply chain an initial development momentum. Industrialization strategy (see Chapter 4 Section 4.3.5.1) and planning at both the central and local government level gave the supply chain a sustained power to grow. On the central government level, multiple FYPs set a clear vision of building a fully-development self-sufficient domestic supply chain. Research and development funding were allocated by MOIIT and MOST to executive the vision. At the same time, local and municipal governments' industrial planning centered around creating manufacturing clusters supported by spatially compact supply chain.

However, industrialization of the PV supply chain is only half of the supply chain development story in China, and it is predicated on knowing how to produce the tooling and materials required by PV producers. In other word, supply chain development is as much a process of innovation as industrialization. The supply chain in China became more and more complete over time because innovation conducted by players in this industry produced science and technology advancement, which allowed them to master knowledge required in producing equipment such as diffusion furnace, PECVC, etc., and materials like EVA. Nevertheless, China's weak foundation in scientific and technological innovation remains a weak link in its quest to build a fully-development self-sufficient supply chain.

On-the-ground research conducted by this dissertation found that benefits associated with a domestic supply chain are multi-fold. It either directly or indirectly lowers PV production cost by providing cheaper tooling and material alternatives. It locks in the cost competitiveness for local PV producers, making it difficult and uneconomical for producers from elsewhere to duplicate the practice. A domestic supply chain also allows PV producers to stay flexible and agile by enabling producers and their suppliers to engage in joint R&D at a low transaction cost. Furthermore, flexibility and agility often lead to higher productivity, which indirectly reduce PV production cost and enhance the producer's competitiveness.

Given the fact that the geographically compact solar PV supply chain is central to the competiveness of the Chinese solar PV industry, the questions for policymakers from around the world are two. First, is building a fully developed self-sufficient domestic supply chain a suitable strategy given the state of their national economies? Second, if yes, then how to do so?

There is no standard answer to the first question. Although the supply chain in China has enabled its domestic PV companies to gain a large cost advantage, supply chain is not for every country.

First of all, China's supply chain is hard to be duplicated elsewhere because it is part of the greater China industrial enterprise. Not everything in the PV supply chain is specifically built for the solar industry; many of them are (e.g. silicon, ingot and wafer, etc), but a good number of them are just another application of China's massive manufacturing industries. For commodities like glasses, electric wires, aluminum frames, Chinese PV producers can take the advantage of the already-exist suppliers. For countries that do not have a solid infrastructure for manufacturing, building a full supply chain from scratch can be costly and inefficient.

Second, even with good pre-existing manufacturing infrastructure, a country's solar PV supply chain is only as good as its innovation capacity. Southeast Asian countries are living testimony of this point. Even with low labor cost and rapidly developing infrastructure, countries like Vietnam and Malaysia still have a supply chain disadvantage to China because of their incapability to master the production method of a few technologically demanding materials and equipment. Although the decision to pursue a full supply chain may as well provide a strategy that countries can use to develop their science and technology strength, it is a long-term project and requires even more investment in R&D infrastructure and education than building the manufacturing capacity. However, countries with strong foundation in science and engineering such as

Japan, many western and northern European countries and the U.S. are well positioned to be strong competitors in manufacturing certain advanced equipment and materials.

Although there is no standard prescription for building an effective supply chain, a few lessons learned from the China's example can shed some light on how to make the endeavor successful.

Firstly, the government has to play a role in supply chain development. As seen from China, market force alone did not create the supply chain. A national vision for a supply chain development is necessary because it sends an assuring signal to the market. By legitimizing the idea of supply chain, it mobilizes human, financial and technical resources to take part in supply chain development. Granted, a supply chain can be developed without a national vision, it is just that an organic supply chain development is likely to be slower and imbalanced in terms of the strength of each link. The role of a national vision is to provide confidence to market players and local policymakers in order to stimulate a speedy and concerted effort.

Secondly, the spatial configuration of the supply chain is as important as its completeness. For a product like solar PV, which has a short production process, a regionally clustered supply chain built around major manufacturers is most effective. Shorter spatial distance between manufacturers and their suppliers creates agglomeration economies that allow players to share infrastructures and common labor pool. They reduce logistics cost and transaction cost related to communication; they spur knowledge diffusion and improve flexibility and agility of both the manufactures and their suppliers.

Thirdly, supply chain development is as much a science and technology matter as an industrial one because modern manufacturing requires advanced equipment and materials (Clark, 2013). Any advancement made in research labs has to be implemented through improvements in production process, which are made possible only through new materials and upgraded equipment. At the end of the day, scientific and technological knowledge is the ultimate enabler of supply chain development. Policies that eye towards building a strong supply chain should also emphasize science and technology education, public R&D, and firm level innovation.

It needs to acknowledge that there are risks related to building a supply chain for a specific industry. An industry-specific supply chain may suffer from “lock-in” or “path dependence” problem (Liebowitz & Margolis, 1995; Martin & Sunley, 2006; Unruh, 2000), where positive feed back loops are formed to reinforce the status quo, making it is difficult for the system to adopt new technologies and to adapt to changes. There are upsides and downsides of path dependence.

On the upside, once an organization (could be a company, an industry, or even a country) has a head start, even by chance, it tends to stay ahead. The rate of return increases rather than decreases (Arthur, 1989, 1990). In the solar PV industry’s context, the fully developed local supply chain cluster first formed in the YRD area, making it an attractive place for solar panel manufacturing. It grew more sophisticated with time and continues to attract more manufacturing capacity. Its sustained attractiveness rooted in agglomeration economies rendered few Chinese and foreign region able to compete.

However, the downside of path dependence is more worrisome. By reinforcing its current position, an organization develops attachment to its technology and sees vested interests rise around the predominant organization structure. It becomes fossilized and resistant to change. These characteristics render the organization vulnerable to new and disruptive technologies. This is an alarming tale to the Chinese solar PV industry and its supply chain. Fortunately, a supply chain can be built flexible to mitigate the negative effects by leveraging a wide variety of suppliers, including both industry-specific suppliers and general suppliers that it shares with other industries. This is harder for technology-specific supplies, such as silicon and wafer in the solar PV industry's case. But it is possible for generic supplies, like glass, aluminum frame, cable, scrubbers, etc. By effectively sharing suppliers, the newly built supply chain can take advantage of suppliers that are flexible enough to supply to multiple industries. The Chinese solar PV supply chain started in exactly this way. Suppliers who had the capability to provide products to multiple industries have endogenous flexibility, which prepares them for future changes that may happen to the industry. By including suppliers like this, a manufacturing industry can build resilience and adaptability to protect itself from disruptive changes. It is also fair to say that the broader a country's industrial base, the more likely that its supply chains are flexible, adaptable and resilient because they have a wide range of industries to draw suppliers from.

CHAPTER 6

CONCLUSIONS, POLICY IMPLICATIONS AND RECOMMENDATIONS

6.1. Summary of Findings and Conclusions

This study examines the solar PV innovation and manufacturing system in China. By studying their history and development mechanisms, this study concludes the following.

Using solar cell lab efficiency, the quality and quantity of solar PV patents, and publications as three innovation indicators, this study finds that in general, China is closing the innovation gap between itself and the world's leading innovators. Unlike what conventional wisdom assumes, this study shows that the Chinese PV R&D community has been actively engaging in basic science research and has produced noticeable outcome in certain technology areas. This finding debunks the myth that China does not conduct any hardcore scientific and technological innovation. However, the progress is uneven across PV technology spectrum. Depending on the choice of innovation indicator, the progress is more pronounced in certain technology areas than in others.

Using solar cell efficiency as an indicator, the gaps between world-record efficiencies and leading Chinese efficiencies have been narrowed significantly in technology areas such as HIT, CIGS, pervoskite and organic solar cell. However, in technologies like CdTe, the gap between China and the developed world is persistent.

Using the number of invention patents granted in China as an alternative indicator, this study finds that the number of solar PV related patents granted to Chinese entities has increased significantly since 2007 and it outpaced the increase of foreign patents. Further examination of patent quality shows that patents granted to Chinese entities tend to have higher lapse rates than their foreign counterparts in six types of technologies, indicating a lower patent quality among the former group. The trend is reversed in eight other types of solar PV technologies. It is found that lower Chinese patent quality tends to correlate with the academic patent holders. Government policies that subsidize patent application and incentive structures within academic are found to be two main reasons responsible for lower patent quality among academic players. Furthermore, a close look at individual technologies, once again, shows an uneven distribution of progress across the technology spectrum. Technologies like HIT, CIGS, OPV, pervoskite, etc. have seen significant increases in patent quantity, whereas little progress has been made for IBC.

A literature review of bibliometric studies about solar technology reveals that Chinese researchers are catching up from behind in terms of publication growth rate, although the absolute number of publications, especially in English language, is still small, indicating a smaller influence of their work.

The reasons behind the increasingly active solar innovation in China are threefold. First, Chinese government has a strategic vision for its solar PV industry, which is to achieve both technological advancement and industrialization along the entire solar PV value chain. It carries out this vision through increasingly nuanced R&D and industrialization planning over multiple Five Year Plan (FYP) cycles. The FYP visions are then implemented by a suite of science, technology and innovation (STI) programs administered by MOST. This suite of STI programs is designed to cover the entire RDD&D cycle of solar PV technologies.

In addition to the national vision and implementation strategy, growing public finance support from the central and local governments coupled with corporate R&D investment from major Chinese solar panel manufacturers fuel the innovation activities in both academia and the industry. Between 2000 and 2015, NSFC invested $26 million to solar PV related basic research at the same time the 973 and 863 Program, two flagship STI programs, poured at least $48 million to large-scale PV specific basic and applied research projects. While the public finance's support to solar PV innovation in China is evident, leading Chinese solar PV manufacturing companies have also established a record of R&D investment. More importantly, in recent years, they have become the heavyweight players in solar innovation as their R&D expenditures dwarf the government spending. However, even with the uptake in both public and private R&D investment, the financial resources they spent are still much smaller than those of their American counterparts. Even though money stretches further in China, the fact that government spending on solar PV innovation in China is less than one-tenth of that of the U.S. and leading Chinese PV manufacturing companies spend less than half of what their American competitors spend on R&D suggests that China is still a good distance behind the world's leading innovators like the U.S. Despite the growing amount of R&D spending, there is a large room for China's to increase its input to the solar PV innovation system.

The third reason for innovation improvement is that solar PV R&D in China benefited from innovation networks that involve both public and private innovation players and connect domestic and international research capacity. Both policy and the market played a role in forming the innovation ecosystem at the macro-level and the technology-specific innovation networks at the micro-level.

The Ministry of Science and Technology (MOST) of China orchestrates a national innovation ecosystem. It uses a set of STI programs as intermediaries to connect the national PV innovation visions and public finance resources with the actually innovation players on the ground. The breadth of the STI programs equals to the entire RDD&D cycle. They purposefully connect academic innovation players with industry players through incentive structures (or even de factor requirements for public-private partnership) in order to cover the full lab-to-market cycle. Driven by the shrinking space for cost competition and the markets' growing taste for high performance solar panels, Chinese companies also increasingly seek to expand their innovation capacity through collaborating with domestic and international academic researchers, forming the foundation of technology-specific innovation networks. This emergence of innovation networks was further solidified by the government's global effort to recruit science and technology experts to come to work in China. A good number of oversea-trained Chinese and foreign national solar PV researchers were recruited by government-led programs such as the Thousand-Talent Program to work in China. They introduced world's leading research methods and cutting-edge scientific concepts to China and significantly narrowed the knowledge gap between China and the West. These recruited PV researchers along with their connections at overseas PV R&D hotspots became an integral part of China's innovation networks. These networks are found by this study to be quintessential to the improvement of China's solar PV innovation capacity and the narrowing of innovation gaps between China and the world-class for a good number of technologies.

In contrast to its increasingly global innovation network, solar PV manufacturing in China thrives on a fully development domestic supply chain.

Similar to innovation, PV manufacturing in China benefited from having a national vision and an industrialization strategy, which centered on building economies of scale and developing domestic supply chain. Both quantitative and qualitative evidence suggests that economies of scale have contributed significantly to Chinese solar PV manufacturers' cost advantage, which led to their global market dominance. Economies of scale was first created and then sustained by a suit of pro-solar deployment policies in Europe, the U.S., China, etc. Growing market demand led to continuous capacity expansion (with an interruption between 2012 and 2014 due to trade wars), allowing Chinese manufacturers to create economies of scale, during which process they kept upgrading their production equipment and materials, which led to higher productivity and lower production cost. In addition, vertical integration allowed manufacturers to internalize outside suppliers to create vertical scale along the value chain. It in turn lowered the transaction cost and eventually lowered the overall production cost.

Speaking of low cost, the quantitative analysis done in this study shows that besides economies of scale through capacity expansion and vertical integration, government financial assistance on access to debt and equity are also casual factors that led to lower PV production cost among large Chinese manufacturers. Unlike what theory suggests, tax breaks and higher levels of R&D investment are not found to be causally link to low cost PV production in China. Nevertheless, one factor that the quantitative analysis was not able to characterize but was fully explored using qualitative data is the development of the Chinese domestic supply chain.

In the era of globalization, the Chinese solar PV supply chain is strikingly local. When the supply chain was first formed, it was mainly made of non-solar-specific suppliers. However, the booming solar PV manufacturing industry created market opportunities that did not only attracted generic suppliers but also spurred the birth and growth of many solar-specific suppliers, many of which developed specialties that filled holes existed previously in the supply chain. Contemporary to the market force was the government policies' repeated calling to build a fully developed domestic supply chain. Research projects that target the technical barriers to domestic production of PV manufacturing tooling and materials were funded by the central government through STI programs. The ultimate goal of these research projects is to master the technical knowledge embedded in the entire solar PV supply chain in order to achieve self-sufficiency.

In a sense, the history of the solar PV supply chain development is a familiar tale. Firms collocate in specific regions to first take advantage of pre-existing suppliers and then co-develop with them. In so doing, they create agglomeration economies that offer benefits ranging from sharing suppliers, diffusing knowledge, to building and utilizing common labor pool and infrastructure (Christopherson and Clark 2009; Florida 2013;

Krugman 1991; Porter and Stern 2001). Found by many previous industry and region-based case studies, agglomeration economies do not only facilitate the development of an industry, it is central to the competitive advantage of the industry and the region it based in (Christopherson and Storper 1986; Gray, Golob, and Markusen 1996; Markusen 1991; Scott and Storper 2007). However, such findings have not been confirmed in renewable technology manufacturing industries, partly because of the young age of these industries. Previous studies about the wind and solar industry approached the issue either from individual firms' perspective (Nahm & Steinfeld, 2014a) or from a pure national policy's perspective (Zhao, Zhang, Hubbard, & Yao, 2013b) rather than from the industry and region's perspective, and many of them paint a rather global picture (Dunford, Lee, Liu, & Yeung, 2012; Lewis, 2013).

The regional study approach is good at teasing out the dynamics between firm strategies and local or regional institutions. However, for the solar PV industry in China, its development is affected surely but not only by local and regional institutions, but also by national institutions given China's long history in central-planned economy, and by international institutions such as global trade and foreign solar deployment policies. What makes this study unique is that it seeks, examines, and adjudicates explanations for the PV industry development at multiple scales.

It is discovered that central government policies are mainly responsible for knowledge development related to the entire solar PV value chain, that is from labs to production lines and eventually to the supply chain.

Regional institutions are weak in the Chinese solar PV innovation system. Most local governments prioritize industrialization before innovation. They repeat the rhetoric about innovation set by the central government and try to mirror some of the STI programs run by MOST, but the intensity of the R&D support is low and not impactful. Nevertheless, there are some encouraging signs. Some farsighted locales such as the City of Suzhou in Jiansu Province and the City of Jiaxing in Zhejiang Province are leveraging innovation as one of the driving forces for their industrial upgrades, although the approaches they use, like setting thresholds for minimum corporate R&D investment and capital intensity, still have a flavor of command-and-control style policymaking.

Universities are found to be participants but not “engines” of solar PV innovation (Fritsch & Slavtchev, 2007; Gunasekara, 2006). They are either incentivized by government policies to work with industry players or approached by them, but this study discovers no evidence showing that universities and other research institutes have either the vision or ambition to define, shape or drive the regional innovation effort.

In contrast to local institutions’ less than prominent role in driving innovation, they are front and center in creating the agglomeration economies of PV production. The initial market momentum to collocate the PV producers with suppliers was later solidified by the establishment of a number of solar-centric industrial parks sponsored by local governments. These industrials parks facilitated the formation of spatially compact industrial clusters around major solar PV manufacturers. These industrial clusters are crucial in explaining Chinese PV manufacturers’ cost competitiveness. As a result of market forces and government policies, the PV supply chain in China grew more complete and robust over time.

The benefits of having a fully developed domestic supply chain are multiple folds. First of all, a domestic supply chain provides Chinese PV manufacturers with cheaper alternative tooling and material options that directly reduce their production costs. Even in cases where Chinese PV producers did not directly buy from domestic suppliers, just the threat to switch forced foreign suppliers to reduce the price of their products, which indirectly reduces PV production cost in China. Secondly, domestic supply chain lowers the transaction cost associated with communication (P. Krugman, 1991a; Williamson, 1999) between suppliers and PV producers and allows the latter to customize their production equipment with the support form the former. Chinese PV manufacturers become more agile, flexible and productive because of this collaborative local learning.

Lastly but importantly, the vertically disintegrated agglomeration economies created by the domestic supply chain lock the cost and logistic advantage within China and gives the country unique infrastructure, business, and knowledge advantages that are difficult to duplicate elsewhere.

Economies of scale and supply chain development are two of the many factors that this study examined in searching for sources of market competitiveness among Chinese PV manufacturers. Five categories of factors were identified to have significant impacts on competitiveness. For example, the previously discussed economies of scale and supply chain development as well as innovation belong to the agglomeration economies category. They are not simply a reflection of individual company's behavior but the characteristics of the structure of the whole industry. In contrast, firm strategy factors like flexibility, process innovation, and management show that despite the structural factors, individual companies have a good amount of leeway in creating competitiveness through their own operation practices. In addition, factors like work ethic, the pragmatic attitude, and the manufacturers' unabashed desire for lower cost all provide important cultural context to understand solar PV manufacturing in China. Besides, macro factors such as access to labor, infrastructure and capital as well as industrial policies, deployment policies, labor and environmental regulations, and government subsidies and incentives all play a role in building the manufacturing strength of the solar PV industry in China.

Nevertheless, the Chinese solar PV industry still has a lot of stubborn weaknesses and faces many challenges. Solar PV R&D in China focuses on short-term commercial success at the cost of long-term scientific innovation. It is largely comfortable with playing a "catch-up" game and has achieved very few scientific and technological breakthroughs. MOST's utilization of the science, technology and innovation programs were inefficient and ineffective because of its lack of policy consistency and continuity, its own less-than-perfect technology forecast, and inaccurate market feasibility assessment. Local institutions, including local governments and universities, have not developed the tenacity to building innovation strength. To make things even worse, the weak innovation capacity jeopardizes the competitiveness of the manufacturing sector and the development of the supply chain, making it difficult for them to gain strength in areas that requires advanced knowledge and manufacturing skills. Besides, the single-minded pursuit of quick commercial success via the low road development strategy (compete for low cost) caused the industry a range of problems from low product quality to poor product performance. It trapped the industry in the low-end market. Last but not least, an overshot of the economies of scale strategy fueled by easy access to capital and local governments' short-term-interest-driven economic development decisions led to rapid but irrational expansions of manufacturing capacity, which eventually landed the industry in the hot water of international trade disputes and forced it to go through a painful industry structuring.

The next section will discuss the policy implications of these findings. They meant to be applicable not only to the solar PV industry but also to socially and environmentally friendly technology-oriented industry in general. The recommendations are crafted with both the developing and developed countries in mind.

6.2. Policy Implications and Recommendations

The policy implications and recommendations of this study touch on three areas. First, lessons about institutional building can be learned from the development course of the solar PV industry in China. Furthermore, policymakers need to be aware of the fact that the development of a new industry should be a synthesized effort across multiple arenas, namely technology innovation, manufacturing, deployment, and supply chain development. As a result, policies targeting those specific areas should be designed in concert with one another to maximize the efficiency of the system. Last but not least, depending on the type of technology, the nature of knowledge, and the development stage of the country in focus, different geographical configurations of production and knowledge network should be considered. Figure 6.1 summarizes the key policy recommendations that this dissertation recommends policymakers to take. The remaining part of this chapter will elaborate on them.

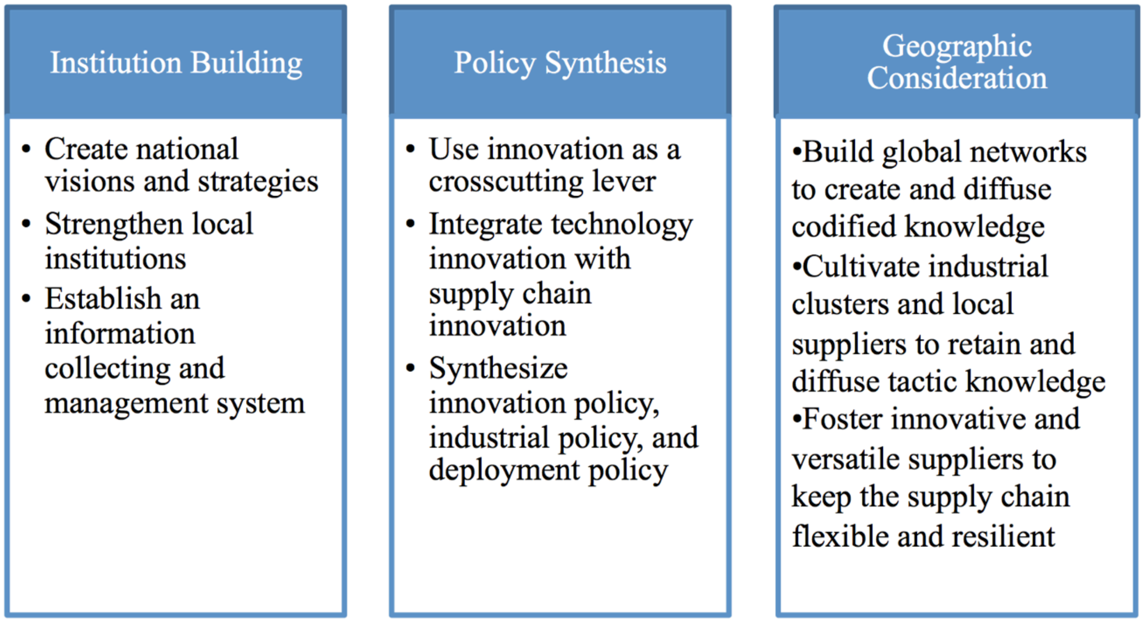


Figure 6.1 Summary of Policy Recommendations

6.2.1. Institution Building

6.2.1.1. National Vision and Strategy

When it comes to developing a new industry, it is important to have a national vision and follow it with a national strategy. As seen time and time again in the discussion of the solar PV innovation, manufacturing and supply chain development in China, setting a vision for technology innovation and industrialization is the beginning point of building an industry. National or federal government bears the responsibility of laying out the national vision. Having a national vision is crucial because above all things, it shows the government’s commitment to the technology and lends it legitimacy going forward. Legitimacy is important for a new and emerging industry if it wants to compete with the incumbents. Once gaining the initial legitimacy, an industry can mobilize human, financial and technical resources to create markets and build acceptance.

An industry can certainly develop in an organic way without having the endorsement from the national or federal government, but an organic development is slower and riskier, and may face many resource constraints. The longer it takes for an industry to garner resources to grow its size and strength, the slower it becomes competitive in the marketplace. The role of a national vision is to provide policy certainties and give confidence to the market in order to stimulate a concerted and speedy effort among as many stakeholders as possible to develop the industry.

Although national visions are more commonly seen in planned-economies like China's, the concept is not alien to a Western audience. The success of the U.S. space program since the 1960s is a good example of what a national vision can accomplish (Cornelius, 2005).

A national vision is meant to be aspirational. In terms of substantive implementation of the vision, a national strategy is recommended. Depending on the technology, different types of strategy should be leveraged. For technologies that are still early in their research stages, a strategy that focuses on technology innovation is suitable. For market-ready technologies, strategies such as building economies of scale, supply chain development, and demand stimulation (i.e. deployment policies such as FITs and investment tax credit for solar) are preferable.

Policy recommendation 1: Create a national vision for technology development and commercialization and follow it with concrete strategies.

6.2.1.2. Local Institution Building

One lesson learned from studying the solar PV industry in China is that a mismatch between national and local institutions can prohibit the innovation and industrial progress. Policies and programs set at the national level are interconnected with local regulatory, innovation and economic development capacities. It is true for federal and centralized systems alike that the local implementation of national policies as well as localities' own "laboratory of democracy" type of experiments are just as important as what happens at the national level (Norton, 2005; Ostrom, 2005). An effective national policy achieves its goal not by micro-managing but through mobilizing resources to the greatest extent possible. Local institutions such as local governments, universities, and regional industry consortiums can at least be the amplifier of national policies. What is more, they can and should be the engine of the regional innovation and economic development machine.

Local governments in the Yangtze River Delta region played a key facilitating role by creating physical spaces and a welcoming policy environment for the solar PV manufacturing clusters in the region. The spatial collocation of suppliers and PV manufacturers was accentuated with the existence of solar-oriented industrial parks, which formed the foundation of an agglomeration economy.

However, the co-location has focused predominantly on the manufacturers and their suppliers, and it has less an emphasis on incorporating innovation players such as universities, research institutes, or high-tech start-ups in the region. On the one hand, local governments were slow in realizing the importance of innovation players. But on the other hand, majority of the universities and research institutes in the region have not demonstrated strong endogenous motivations to take part in the regional agglomeration economy. As a result, the region's rapidly growing manufacturing capacity outpaced its innovative capacity. This does not mean that industries would necessarily face a set back when they are not sufficiently supported by the embedding regional innovation systems. The Chinese solar PV industry's example shows that in the era of globalization, firms and industries can escape unfavorable conditions by reaching beyond their physical boundaries to other domestic regions or even overseas for innovation capacity and be successful. However, that strategy does mean that the regions where firms and industries locate miss a big opportunity to build, strengthen, and upgrade their own regional innovation systems and support innovation players in their territories. Given the fact that SME suppliers, unlike the big manufacturers they supply to, are less likely to have national or international research networks, the absence of local innovation capacity puts a constraint on their ability to advance technologically, which would eventually impact the entire region's competitiveness.

With that being said, local governments should be proactive in creating physical space to incentivize manufacturing firms to collocate with their peers and suppliers. Agglomeration economies created by such approach are center to the competitive advantage of an industry and the region it locates in. More importantly, technology providers, innovation players, and high tech suppliers should also be in the mix, in order to create long-term competitiveness for the industry and allow the region to share the full benefit for having supported the industry. On the flip side, innovation players like universities and research institute should actively seek opportunities to participate in the physical agglomeration economies of production and the virtual value flow that includes knowledge development and diffusion. They can do so by establishing scholarly or internship programs with local firms (Yingli Solar has such programs with local universities), forming research partnerships (such as multiple CAS institutes' collaborating relationships with leading Chinese PV manufacturers), or even building incubators in local industrial parks to transfer products developed in research labs to production lines, which has been seen in industries like IT and biotech but not yet in solar PV.

Policy recommendation 2: Utilize local governments' facilitating role to develop agglomeration economies of production through physically and virtually connecting manufacturing and innovation players.

Another area for local institutions to improve upon is how political dynamics between firms and local governments are handled. One big lesson learned from the development of the PV manufacturing sector is that local governments, in pursing economic development in their territories, sometimes bent over to firms they deemed as important and extended sizable incentive packages that compromised the financial healthiness of their jurisdictions and locked themselves into a vested interest with the firms, which only became more entrenched over time. Industrial development is as much a political activity as an economic one. Firms and their local governors engage in constant bargaining over how to distribute the cost and risk as well as the profit and benefit of the economic activities (Christopherson and Clark 2009). The swing of political power can go both ways and local governments could be vulnerable politically in their relationships with firms. It all depends on which party has more of the resources that the other party wants. For localities that yearn for more economic development and jobs, they are susceptible to firms' lobbying power. They become captive to two things: the ideal scenario that they long for and the firms that they thought are going to bring the ideal to reality.

Local governments need data-driven rational decision-making to break this psychology. They should make decisions based on what is likely to happen, supported by empirical evidence and sound policy analysis, instead of on what they hope will happen. They need evidence-based policy to decide whether using the collective resources to support a particular firm, an industry or even an innovation system will actually benefit the majority of their constituencies. A good example of such policymaking practice can be found in cities such as Jiaxing. The municipal government of Jiaxing bases the amount of tax incentives firms will receive on their actual performance, usually measured in tax revenue contributed, number of jobs created, etc. Measures like this could enable a prudent and effective use of public finance.

Policy Recommendation 3: Use rational, data-driven policy analysis to strengthen local governments' decision-making capacity.

6.2.1.3. Information Collection and Management

A good data collection and management system is the foundation of evidence-based policymaking. Without good information on how resources are allocated and what outcomes they yield, past lessons and experience cannot shed light on future decision-making. It could lead to huge waste of public and private resources.

This study highly recommends that countries develop and perfect their public data collection and management system and make it capable of providing nuanced information for program evaluators to study the effectiveness and efficiency of various policy programs. In addition, this study wants to make a plea to countries, especially developing countries, to allow more transparency in their information system and make it easy and free for the public to access. Good governance and sound policy-making can only be achieved through accountability, and having transparency is the necessary first step towards these goals.

Policy recommendation 4: Establish an accurate, comprehensive, and transparent public information collection and management system, with open access to the system.

6.2.2. Linkages between innovation, manufacturing, and deployment

6.2.2.1. Innovation as A Crosscutting Strategy

The discussion of strategies to develop a socially and environmentally friendly technology-based industry highlights the connection among innovation, industrial and deployment policies. Rather than treating them as stand-alone policy arenas, policymakers should carefully consider the synergistic effect embedded among the three.

The example of the Chinese PV industry highlights the problem often faced by developing countries, which is that, in the long term, their manufacturing capability is only as strong as their innovation capacity. Gaps in scientific and technical knowledge result in weak links or even holes in the domestic supply chain, preventing the industry from achieving its full competitive potential. Developed countries face a different problem. Often, they have the innovation capacity in both the technology R&D and manufacturing stage but experience difficulties scaling up their technologies in an economical way.

The problems faced by developing and developed countries are essentially two sides of the same coin. They both reflect a mismatch of innovation and manufacturing capacity. For developing countries, they usually make market-ready technologies, but their weak science and technology foundation constrains their manufacturing capabilities. On the other hand, although developed countries' manufacturing sectors are usually sophisticated enough, the technologies they produce sometimes are too nascent or too technically complex to be commercially viable. The case with American thin-film solar PV producer Solyndra is an example of it (Kao, 2012). Then the question for them becomes how to gauge technology innovation to the market.

Challenges faced by both worlds point out the importance for policymakers to not treat technology innovation, manufacturing, and deployment in isolation. Rather, they should strategize how to integrate them in order to push innovation down the supply chain and at the same time allow market feedback to inform innovation.

For developing countries, innovation is the connective tissue of many policy areas and therefore, promoting innovation should be a crosscutting strategy. Developing countries can increase their manufacturing capability by funding R&D projects to target technical issues that constrain the manufacturing and supply chain development. Knowledge developed along the way can in turn strengthen the overall innovation capacity and enable more scientific and technological advancement. In addition, local governments should be proactive in fostering close ties between industry players and academics in their territories, to engage them in R&D partnerships, and to make them attentive to each other's resources and demands.

Policy recommendation 5: Use innovation as a crosscutting strategy at both the national and local level to build strength across the entire chain of technology R&D, manufacturing, and supply chain development.

6.2.2.2. Innovation in Technology and Supply Chain

For developed countries, there is a dilemma. On the one hand, as the inventors of advanced technologies, they should not lower the quality of their technologies simply to make them more affordable in the marketplace. But on the other hand, technical complexity and high cost can lock the providers of advanced technologies out of the market. The solution to this dilemma lies in the integration of technology innovation and supply chain innovation. First and foremost, a country's innovation system should always be forward-looking; but when it comes to transferring a technology from lab to production line, the manufacturers have to be sensitive to cost. Fortunately, as the Chinese example shows, the manufacturers do not have to (and cannot) do it alone. Instead, it should be a concerted effort between technology manufacturers and their suppliers because much of the technology advancement on paper is actually realized through new tooling and materials. They make it possible to incorporate new functions and features into the products and are responsible for delivering the innovative content. With the same ingenuity, tooling and material suppliers can also discover ways to reduce cost without compromising product quality. At the end of the day, the delivery of a marketable new product is a joint venture between manufacturers and suppliers. Often time, discussions are built around the role of the former, but from a systematic perspective, it is equally important to support the building of innovation and manufacturing capacity of the latter.

Suppliers are often small and medium enterprises (SMEs). Because of their size, they frequently find themselves in disadvantaged positions vis-à-vis large firms. This market-power inequity is partially responsible for them being exploited and squeezed by large firms (Christopherson and Clark 2009; Rutherford and Holmes 2007). In order to improve the innovation and manufacturing strength of SME suppliers, the market power inequity needs to be corrected, or at least alleviated. One possible way to do so is to treat SMEs as large firms, to allow them to form their own networks in order to gain power to influence policies, to obtain access to innovation resources within and beyond their own regions, and to effectively share or pool resources as a group to overcome the disadvantages associated with their relatively small individual size.

Policy recommendation 6: Integrate technology innovation with supply chain innovation. Build innovative strength among suppliers that allows them to help commercialize technology advancements achieved by manufacturers.

6.2.2.3. Demand-Pull and Supply-Push Virtuous Cycle

Besides the linkage between innovation and manufacturing policies, there is also a synergistic effect between them and deployment policies. In the case of Chinese PV industry, deployment policies in Europe and the U.S. were partially responsible for creating the initial market, and the ramp up of FITs in China in the wake of the trade wars helped absorb the excess capacities and bailed the industry out from an implosion. Policymakers can learn a lesson from the Chinese example to proactively design a set of synergistic policies that foster both the production and consumption of a new technology to create a “demand-pull and supply-push” virtuous cycle (Brown et al., 2007). Policies that tackle just one but not the other will inevitably leave the industry in a vulnerable position.

Policy recommendation 7: Use innovation, industrial and deployment policies in synergy to create a demand-pull and supply-push virtuous cycle.

6.2.3. Localization vis-a-vis Globalization

6.2.3.1. Global Networks for Codified Knowledge

There is an interesting dynamic between localization and globalization. On the one hand, government policies' push to build a domestic supply chain has proven to be tremendously beneficial to the solar PV industry in China and has created a spillover effect to technology innovation along the PV supply chain. Highly concentrated industrial clusters around major solar PV producers have made communication between producers and suppliers easier and the creation, acquisition, accumulation and utilization of knowledge faster. Logistical costs are also lower because of the local supplier chain. These advantages enabled by geographical proximity are rather sticky (Ernst, 2002; A. Markusen, 1996). It is fair to say that the manufacturers' physical supply chain is becoming more and more localized. However, on the other hand, the virtual supply chain, i.e. the knowledge flow, is getting increasingly globalized. Chinese researchers and PV manufacturers benefit from being part of the global knowledge network. The ability to work with foreign scientists, research institutes and to recruit overseas trained experts to come and work in China has dramatically narrowed the scientific knowledge gap between China and the developed world.

Evidence suggests that globalization is not the only answer to questions related to innovation and economic development. Depending on the type of knowledge and technology at hand, players should choose different geographical configurations of network and supply chain that best suit their pursuits.

For codified scientific knowledge, a global network is beneficial for two reasons. First, scientific knowledge can be communicated through writing and teaching relatively easily. But more importantly, a global knowledge network breaks the path dependence of scientific research and creates an environment where different ideas meet. Therefore, from a science, technology and innovation policymakers' standing point, innovation networks that connect different knowledge development clusters should be encouraged. These networks should cover both a wide geography and a diverse background. Personnel exchange between different institutes, industries, and countries should be supported. Programs such as the Thousand-Talent Program are good practices in terms of facilitating knowledge diffusion. Other programs that exchange short-term scholarship are also preferable.

Policy recommendation 8: Promote and support science and technology innovation networks that connect a wide range of personnel from around the globe.

6.2.3.2. Local Industrial Clusters for Tacit Knowledge

However, skills and know-how embedded at individual level, a.k.a. tacit knowledge, are difficult to transfer without in-person interactions and are lost at a fast rate (Argote & Darr, 2000). As a result, a virtual global network is not as suitable as a physical local network for their diffusion. The truth of the matter is, in an era where manufacturing is becoming increasing automated, what differentiates one factory from the next is not what machine it uses (because automation standardizes the manufacturing process), but how it uses the machine. In other words, the tacit knowledge embedded in the interaction between machines and people who designed and operated them makes a huge difference. This type of knowledge is extremely contextual and local because of the idiosyncratic nature of the knowledge development process and the personal touch that the knowledge developers put on it. Only people who are closely involved understand why the knowledge was developed in the very first place and how to use it most effectively (Kogut & Zander, 1992). Knowledge like this can certainly be diffused, but only via in person hands-on exchange; the more geographically removed the learning relationship is, the harder it is to master the gist of the knowledge.

The best way to retain and diffuse local tacit knowledge is to build a local industrial cluster that actively engages in the development and utilization of the knowledge. In this tacit knowledge network, the tooling and material suppliers should play a central intermediary role. In the industrial cluster setting, suppliers are likely to work face-to-face with multiple manufacturers to develop new equipment and material. The tacit knowledge they learn from the in-person interaction with one manufacturer can be passed on to the next manufacturer they work with. In so doing, they become the media of disseminating tacit knowledge, and once again, this intermediary role highlights the importance of SME suppliers in the development of a technology-based industry.

Policy recommendation 9: Support the development of industrial clusters, and foster suppliers to be local tacit-knowledge diffusion intermediaries.

Besides the nature of knowledge, the type of technology also matters. For a technology like solar PV, which entails a relatively short production process (six steps in solar cell production, five steps in panel assembly) but has high quality requirements, a local supply chain is not only feasible but also more suitable for quality and cost control purpose. But for technologies that are technically more complex or has a longer production process, a global production network may be preferred.

6.2.4. Supply-chain resiliency and adaptability

In the process of supply-chain development, policymakers and the industry need to be aware of the danger of "lock-in" and "path dependence" because they render the industry and its supply chain vulnerable to new disruptive technologies. Supply chain resiliency and flexibility are necessary conditions to avoid such situation.

From the industry's perspective, its supply chain can be built flexible by drawing from a wide variety of suppliers, including both industry-specific suppliers and general suppliers that it shares with other industries. By effectively sharing suppliers, the newly built supply chain can take advantage of suppliers that are flexible enough to supply to multiple industries. These suppliers have innate flexibility to begin with and often develop a diverse product line, which prepares them for future evolution of the economy.

By including suppliers like this, a manufacturing industry and its supply chain can become resilient and adaptable to technological change that may happen in the future.

From technology manufacturers' perspective, it is a good idea to develop a supply network instead of a linear one-to-one supplying relationship with specific suppliers. By diversifying the supplying relationship, manufacturers build resilience and flexibility into their networks. From suppliers' perspective, they should also embrace the idea of diversification by exploring relationship with multiple industries. By putting eggs in multiple baskets, suppliers increase their chances to survive even if one industry tanks. The survival of suppliers means more than just the continuous existence of individual firms. Suppliers are the foundation of the broader manufacturing economy; their continuous growth preserves the industrial infrastructure, the manufacturing capability, and the technical know-how of multiple industries.

To echo the point made before, given the importance of suppliers, policymakers should treat them not as secondary players but develop them as equals to large manufacturers. Suppliers should be able to develop their own R&D capacity, establish a diverse collection of products, have their own network of buyers and suppliers, and form enough political cloud to influence policymaking. In so doing, the suppliers can become the enablers of a resilient, flexible and adaptable supply chain.

Policy recommendation 10: Build a resilient supply network by fostering innovative and versatile suppliers with networks to access innovation, business and political resources.

By offering the above policy recommendations, this study hopes to contribute something useful and executable to the development of current and future socially and environmentally friendly technology industries.

APPENDIX A

SUMMARY OF INTERVIEWS AND SITE VISITS

Table A.1 Summary of Semi-structured Interviews

Interviewee ID	Affiliation	Sector
1	Suntech, previous employee	Manufacturing
2	Blue Sky Solar (China), chief engineer	Manufacturing
3	Nankai University, professor	Technology R&D
4	CTIG, researcher	Technology R&D
5	Energy Research Institute (ERI), senior analyst	Policy/Consulting/Industry Association
6	State Council Development Research Center, researcher,	Policy/Consulting/Industry Association
7	China Renewable Energy Industry Association (CREIA), policy director	Policy/Consulting/Industry Association
8	BNEF, senior analyst	Policy/Consulting/Industry Association
9	Tianjin University Technology Transfer Office, director	Technology R&D
10	Solar unser	Deployment
11	Tianjin EcoCity, sustainability director	Deployment
12	Natural Elements Capital (Private equity firm), solar director	Deployment
13	Yingli Solar, employee	Deployment
14	ERI, retired senior analyst	Deployment
15	Continental Automotive (Austria); technical project leader	Technology R&D
16	BNEF solar, lead solar analyst	Policy/Consulting/Industry Association
17	New South Wales University, professor	Technology R&D
18	Suntech, employee	Corporate R&D
19	TEBD Solar, employee	Manufacturing
20	NeoSolar (Taiwan), R&D director	Manufacturing
21	JA Solar (China), employee	Manufacturing
22	Fengyuan Module (China), employee	Manufacturing
23	Haitai Module (China), employee	Manufacturing
24	Jinko Solar (China), employee	Manufacturing
25	Canadian Solar (China), employee	Corporate R&D
26	Zhongli Talesun (China), employee	Manufacturing
27	GCL Poly (China), employee	Manufacturing

Table A.1 Contniued

Interviewee ID	Affiliation	Sector
28	Yingli Solar (China), employee	Manufacturing
29	Hanwha Solar (China), employee	Manufacturing
30	Suntech, former employee	Manufacturing
31	A medium size Chinese company, CTO	Manufacturing
32	ZNSHINE Solar, VP	Manufacturing
33	HIS, analyst	Policy/Consulting/Industry Association
34	Taiwan Analytical, analyst	Policy/Consulting/Industry Association
35	Solar Media, analyst	Policy/Consulting/Industry Association
36	Yingli Solar (China), employee	Deployment
37	Australia Renewable Energy Council, policy director	Policy/Consulting/Industry Association
38	CREIA, general secretary	Policy/Consulting/Industry Association
39	Shanghai Solar Energy Research Center, director	Technology R&D
40	Total, new energy division, technology, operations and projects division; technology cost manager	Manufacturing
41	Fraunhofer Institute for Solar Energy Systems (Germany), researcher	Technology R&D
42	FHR Centrotherm Photovaltaics Group (Germany), researcher	Technology R&D
43	ERI, director	Policy/Consulting/Industry Association
44	Tsinghua University, Institute of Environment Energy and Economics, director	Policy/Consulting/Industry Association
45	Chinese Academy of Sciences (CAS), Institute of Electrical Engineering (EEI)	Technology R&D
46	Yingli Solar, CTO	Corporate R&D; Manufacturing
47	Hanergy, senior manager	Technology R&D
48	Hanergy, senior supervisor	Manufacturing;
49	Tsinghua University , assistant professor	Policy/Consulting/Industry Association
50	State Grid, director	Policy/Consulting/Industry Association
51	BNEF, analyst	Policy/Consulting/Industry Association
52	Nankai University, professor	Technology R&D

Table A.1 Contniued

Interviewee ID	Affiliation	Sector
53	Trina, CTO	Corporate R&D; Manufacturing
54	Jinko, CFO	Manufacturing;
55	Jinko, investor relations director	Manufacturing;
56	Jinko, customer service director	Manufacturing;
57	GCL Poly, vice president	Manufacturing;
58	GCL Poly, assistant to GM of strategy and operation	Manufacturing;
59	CAS, Shanghai Microsystem Institute, researcher	Technology R&D
60	China Development Bank, New Energy Division, deputy director	Financial Institute
61	CREIA, general secretary	Policy/Consulting/Industry Association
62	National Energy Agency, director of solar energy	Policy/Consulting/Industry Association
63	Ministry Of Industry and Information Technologies (MOIIT), director of Solar Office	Policy/Consulting/Industry Association
64	Chinese Academy of Science and Technology for Development (CASTED), researcher	Policy/Consulting/Industry Association
65	Longyan Solar (advanced solar power ASP), chairman	Corporate R&D; Manufacturing
66	Shanghai New Energy Industries Association (SNEC), general sectary	Policy/Consulting/Industry Association
67	Ministry Of Science and Technology, New Energy Division, director	Policy/Consulting/Industry Association
68	Peking University, professor	Technology R&D
69	State Grid, director	Deployment
70	Energy Research Institute, researcher	Policy/Consulting/Industry Association
71	Trina Solar, CEO	Manufacturing
72	China Solar PV Industry Association, vice chairman	Policy/Consulting/Industry Association
73	MOST, cheif PV Scientist	Technology R&D
74	GCL Poly, VP	Manufacturing
75	China Commerce Bank, banker	Deployment
76	SUNGROW, VP	Manufacturing
77	GD Solar, VP	Manufacturing
78	Export-Import Bank of China, director	Policy/Consulting/Industry Association

Table A.1 Contniued

Interviewee ID	Interviewee ID	Interviewee ID
79	Yingli Solar, CFO	Manufacturing
80	Venture capitalist	Financial
81	Zhejiang Xiuzhou Industrial Park, director of Solar Office	Policy/Consulting/Industry Association
82	Zhejiang Xiuzhou municipal government, deputy mayor	Policy/Consulting/Industry Association
83	Flat Glass, chairman	Manufacturing
84	Flat Glass, PV installer	Deployment
85	Sunprem Solar, chairman	Manufacturing
86	Rooftop solar project in Jiaxing, PV installer	Deployment
87	Jinko Solar, director of process design	Manufacturing
88	Jinko Solar, R&D director	Manufacturing
89	Jinko Solar, manufacturing director	Manufacturing
90	Wuxi DRC Energy, director	Policy/Consulting/Industry Association
91	Wuxi DRC Economic and Information Commission, Industrial Division, director	Policy/Consulting/Industry Association
92	Wuxi New Energy Industries Promotion Committee, deputy director	Policy/Consulting/Industry Association
93	Nankai University, professor,	Technology R&D
94	US Department of Commerce, Representitive	Manufacturing (Trade)
95	First Solar (U.S.), representative at Beijing	Manufacturing
96	JA Solar, CFO	Manufacturing
97	JA Solar, VP of supply chain	Manufacturing
98	Canadian Solar, CEO	Manufacturing
99	Canadian Solar, supply Chain director	Manufacturing
100	Trina, CFO	Manufacturing
101	Trina, supply chain director	Manufacturing
102	Sunergy, business strategy director	Manufacturing
103	The 48th Research Institute affiliated cell production facility, manager	Manufacturing
104	Deputy director of The 48th Research Inst.	Manufacturing
105	CREIA, director of solar policy	Policy/Consulting/Industry Association
106	Thousand-Talent Association, director	Policy/Consulting/Industry Association
107	Thousand-Talent Association, deputy director	Policy/Consulting/Industry Association
108	State Grid Nanjing Research Institute	Deployment
109	State Grid Nanjing Research Institute	Deployment
110	U.S. National Renewable Energy Laboratory, Solar Division director	Policy/Consulting/Industry Association

Table A.1 Contniued		
Interviewee ID	Affiliation	Sector
111	Patent Lawyer based in the U.S.	Policy/Consulting/Industry Association
112	Patent Lawyer based in China	Policy/Consulting/Industry Association

Note: Interview 1 - 42 were conducted by the author individually. Interviews 43 -112 were conducted by the Stanford research team as part of the Stanford China Project.

Table A.2: Summary of Site Visits

Tour ID	Type of visit	Entity
1	Workshop tour	Blue sky Solar
2	Company presentation and tour	GCL Poly
3	Company presentation and workshop tour	Canadian Solar
4	Lab Tour and rooftop solar project	Shanghai solar research center
5	Company presentation and workshop tour	Shanghai Shenzhou New Energy Development Co. Ltd
6	Industrial park visit	Shanghai Nanhui Industrial Park
7	Lab tour	18 Institute in Tianjin
8	Lab tour	CAS EEI
9	Lab tour	Yingli Solar; Baoding
10	Workshop tour	Yingli Solar; Baoding
11	Lab tour	Trina Solar, Changzhou
12	Workshop tour	Trina Solar, Changzhou
13	Industrial park visit	Trina Solar, Changzhou
14	Workshop tour	LongYan Solar (ASP)
15	Lab tour	CAS Shanghai MicrosystemInst.
16	Lab tour	Nankai University
17	Company visit	Hanergy
18	Company visit	State Grid Control Room
19	Industrial park visit	Xiuzhou Industrial Park
20	Workshop tour	Flat Glass (Xiuzhou)
21	Rooftop solar project site tour	Flat Glass rooftop
22	Workshop tour	Sunprem
23	Rooftop solar project site tour	Jiaxing, Zhejiang
24	Workshop tour	Jinko Solar
25	Workshop tour	Canadian Solar Factory, Suzhou
26	Workshop tour	Sunergy factory, Nanjing
27	Workshop tour	48th Institute

Note: Site visit 1 - 7 were conducted by the author individually. Site visit 8 -27 were conducted by the Stanford research team as part of the Stanford China Project.

APPENDIX B

SUPPLEMENTARY MATERIALS TO CHAPTER 3

Exhibit 1: State Key Laboratory of Photovoltaic Material and Technology at Yingli*

History:

- Applied for SKL in 2009
- Awarded SKL in 2010
- Certified by MOST and assumed operation in 2013

SKL Overview:

- R&D team: 150 people
- Research project span: 3-5 years
- Research partners:
    - Chinese institutes
        - Chinese Academy of Sciences: Institute of Semiconductor
        - Chinese Academy of Sciences: Institute of Electronic Engineering
        - Chinese Academy of Sciences: Institute of Microelectronics
        - Tsinghua University Department of Material Science
        - Beijing University of Aeronautics and Astronautics
        - Hebei University
    - Overseas institutes
        - Energy Research Center of Netherland (ECN)
        - SINTEF of Norway
        - University of New South Wales
        - Solar Energy Research Institute of Singapore (SERIS)

SKL Research Structure and Sample Projects:

- Group 1: Silicon material science research
  - Develop new approach to produce poly-silicon
- Group 2: Ingot production technology research
  - Research method to grow and crystalize ingot in a more efficient way and with higher quality
- Group 3: Wafer slicing technique research
  - Develop techniques to reduce the thinness of wafer layer from 180mm to 150mm
- Group 4: Solar PV cell research
  - Surface textuation
  - Iron implantation: p-n junction
  - PERC cell structure
- Group 5: Solar PV module research
  - Improve PV module lifetime and reduce degradation rate.
- Group 6: Solar PV System research
  - Inverter: Design smart inverter to optimize solar array to maximize
  - output voltage
  - Junction box: Design smart junction box for micro-inverter integration
  - Energy storage: Develop lying wheel energy storage technology
- Group 7: Simulation research
  - Develop simulation software to facilitate solar cell efficiency improvement

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of the Stanford China project by the author.

Exhibit 2: State Key Laboratory of PV Science and Technology at Trina*

History:

- Applied for SKL in 2009
- Awarded SKL in 2010
- Certified by MOST and assumed operation in 2013

SKL Overview:

- R&D team: 139 engineers and 200 technicians
- Research project span: long term
- Research partners:
    - Chinese institutes
        - Chinese Academy of Science: Institute of Microsystem and Information Technology
    - Overseas institutes
        - Solar Energy Research Institute of Singapore (SERIS)
        - Australia National University
        - Universidad Politécnica de Valencia

SKL Research Structure and Sample Projects:

- Module Business Unit (MBU): 90% of the total budget and people goes into this category
    - PV material research:
        - Research method to improve the purity of silicon production
        - Develop better techniques for ingot growth
    - Solar cell: develop new cell structures and improve their efficiency in the following technology categories
        - IBC
        - HIT

        - Bi-facial solar cell
        - P-type solar cell
        - N-type solar cell
    - Solar PV module:
        - Double-glass module
    - System Business Unit (SBU)
        - Micro-inverters: allow solar PV to generate AC directly, unlike conventional PV that has to generate DC first and then be inverted to AC.
    - Energy Storage Business Unit (ESBU)

Trina only innovation

- World record 20.8% efficient mass-produced multi-crystalline cell
- IBC cell: 24.4% lab efficiency
- Mass-produced P-type PERC cell
- Big area cell: increased cell area from $125mm^2$ to $150\ mm^2$

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of the Stanford China project by the author.

Exhibit 3. Innovation at Canadian Solar (CSI): Middle of the Road Innovator*

Solar Cell R&D portfolio:

1. N-type solar cell:
    - Long term project aiming at improving cell efficiency
    - 4 bus bar cells: an improvement from conventional 3 bus bar cells. It is of similar cost but higher efficiency.
    - CSI in 2013 became the leader of 4BB by installing a 15MW production line.
    - 5 bus bar cells are under development as of May 2015.
2. Black silicon cell:
    - Developed its own patented black silicon technology
    - Use a low-cost chemical etching approach in commercial production
    - Currently has a 5MW black silicon production, with 0.3% efficiency gain over conventional C-Si cell.
3. ELPS cell:
    - A high efficiency P-type mono-crystalline cell featured Metal Wrap Through (MWT) design.
    - Collaborated with ECN from the Netherlands to develop the first prototype.
    - The attempt to mass-produce ELPS failed because the production cost is too high.
4. PERC:
    - Mass production of PERC cell.

Solar Module R&D portfolio:

1. Anti-reflective coated glasses
2. Encapsulation:
    - Replace the back EVA layer with a functionally similar but cheaper encapsulation material.

3. Printing and stringing equipment
    - Co-developed a new printing and stringing equipment with Chinese domestic tooling manufacture to allow thinner and taller silver paste to be painted on its 5 bus bar cell.

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of the Stanford China project by the author.

Exhibit 4: Innovation at Sunergy: Inventor of PERC, but falling behind in commercialization*

PERC History at Sunergy:

- Dr.Zhao Jianhua invented PERC cell when working at University of New South Wales in Australia. He holds the world record on PERC cell efficiency.
- In 2008, Dr. Zhao brought PERC prototype to Sunergy and became the CTO of the company.
- The first two generations of PERC cells developed at Sunergy failed to achieve commercial production, because of high production cost.
- In 2011, the 3rd generation PERC made a switch from using PVC to screen printing, which in turn lowered the cost to a competitive level.
- In 2012, Fraunhofer certified the 3rd gen PERC cell at a 20.3% efficiency.
- PERC production process is relatively simple compared to other high efficiency silicon-based cells. It only requires adding two additional equipment – an ALD (Automatic Layer Deposition) and a laser machine – to a conventional C-Si production line.

The PERC cells produced at Sunergy

- High efficiency: 20.5% to 20.8%
- 5 bus bars
- Features of the front side of the cell:
    - Patented design of unevenly applied silver paste
    - Gradient distribution of fingers
- Features of the back side of the cell, which is the secret weapon of PERC:
    - Deposit a thin layer of silicon nitride on the back (10 nano-meter)
    - Regular cells only deposit on the front side, but PERC deposit it on both sides.

    - Use laser to remove Al_2O_3 and SiN_4
- Sunergy holds multiple patents

The economics of PERC at Sunergy

- Cost increase: ¥ 0.3 to ¥ 0.5 increase out of 10RMB mono-C cell. i.e. only 3-5% increase in cost.
- In ¥/W term, PERC cell is ¥ 4.7-4.8/W, comparing to conventional cell which is 4.4 to 4.5

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of the Stanford China project by the author.

Exhibit 5: Innovation at Advanced Solar Power (Long Yan): Ambitious R&D Upstart*

Advanced Solar Power (ASP, known as Long Yan in Chinese) at Hangzhou, Zhejiang Province is the leading innovator and producer of CdTe solar PV in China. It was founded by Dr. Xuanzhi Wu, who still holds the world efficiency record for the CdTe solar cell he developed while working at the U.S. National Renewable Energy Laboratory (NREL). The key technology that differentiates ASP from its major global competitor First Solar is its use of the Close Space Sublimation (CSS) method to produce CdTe cells, which increases the speed of the chemical compound deposition. In addition to solar cell research, ASP also works with domestic Chinese tooling manufacturers to develop equipment used in commercial CdTe production.

Despite its promising technology, ASP is still not a formidable competitor to First Solar. Its R&D investment is only 10% of that of First Solar[1]; its mass-produced solar cells are 2-percentage point lower in efficiency than First Solar's predominant technology; ASP has only 30MW manufacturing capacity by 2014, compared to First Solar's whopping 1.8GW capacity. Exhibit 5 provides an overview of ASP's innovation effort.

CdTe solar cell innovation at Advanced Solar Power:

- Key technology: Close Space Sublimation (CSS) method prepared CdTe
- Mass production cell efficiency: 12%, 2% lower than First Solar's main product
- Production capacity: 30MW

  Key figure: Chairman Dr. Xuanzhi Wu
- 30 years of solar PV research experience, including 20 years at U.S. DOE's National Renewable Energy Laboratory
- CdTe efficiency world record holder R&D spending
- Cumulatively by 2013, $30M, 10% of First Solar's R&D spending

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of Stanford China project led by the author.

Exhibit 6: Innovation at Hanergy: Innovation through mergers and acquisitions*

Innovation structure at Hanergy

- Global R&D Center located in Beijing, China, which manages Hanergy's technology profile including
  - CIGS
  - GaAs
  - a-Si

Majority of the actual R&D work are conducted overseas, in R&D labs at the firms they purchased

- SoliBro
  - Glass-on-glass based classic CIGS modules, using Co-Evaporation method
  - 20.7% lab efficiency
  - 14% production efficiency
- MiaSole
  - CIGS with spadering technology.
  - Spadering technology is a deposition method that uses plasma to strike solid metal target to release particles and deposit them onto substrates. It is a faster deposition process although with a lower efficiency.
  - The end product is lighter, about $4kg/m^2$, and more flexible
- Global Solar
  - CIGS prepared with co-evaporation approach and flexible substrate
  - The firm company aimsto commercialize the flexible substrate CIGS.
- Alta Devices
  - GaAs
  - Record holder of single junction thin film solar cell
- Apolo Solar
  - a-Si

Domestic Chinese R&D collaborators

- Tianjin University: Professor Wang Chengshan
- Nankai University: Professor Zhao Ying

  Innovation goal: bring down the cost of lightweight thin film cells.

* Note: Data collected as part of the Stanford China Project. Analysis in this exhibit is done as part of Stanford China project led by the author.

Table B.1 MOST 973 and 863 Program Investment in the Past 3 FYP Cycles by Technology*

Technology	10th FYP		11th FYP		12th FYP		Technology Total (M$)
	973	863	973	863	973	863	
a-Si	2.4		2.4	2.3	4	3.2	14.4
DSSC	2.4		2.4	1.6			6.5
CdTe		3.2		3.9		1.6	8.7
CIGS		3.5			4.8		8.3
HIT				0.3		4.8	5.2
Black Silicon					4.8		4.8
PERC						N.A.	N.A.
Total	4.8	6.7	4.8	8.1	13.7	9.7	47.8

* Note: Data collected and analyzed as part of the Stanford China Project.

Exhibit 7. HIT World and Chinese Efficiency Records*

All the world record efficiencies of HIT solar cell are from Sanyo in Japan. The company started to develop HIT since 1980s. Since its breakthrough of 20% efficient HIT solar cells of 1 cm^2 in 1994, Sanyo has been steadily improving the efficiency by modifying the cell structure. After Sanyo became part of Panasonic Group in 2010, it announced the efficiency record of 24.7% in 2013 and a major increase of 25.6% in 2014 with its HIT+ IBC technology. For mass production, Sanyo started to produce the commercial HIT solar modules of 17.3% efficient in 1997. In 2011, the efficiency was further enhanced to 19%.

China is a latecomer to HIT research; serious research effort did not start until the 11th FYP where MOST invested in two HIT-related 863 Programs. The research group led by Wenjing Wang at CAS IEE reported an efficiency of 17.27% for small-scale HIT cell in 2008. Its joint R&D with Chaori Solar produced a 125mm by 125mm HIT cell of 20.25% efficient in 2013. In the same year, Zhengxin Liu's group at CAS SIMIT produced a 125mm by 125mm HIT cell of 20.13% efficiency.

* Data collection and initial analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.

Exhibit 8. CIGS World and Chinese Efficiency Records*

World record of CIGS as of December 2014 was 21.7% and is held by ZSW Centre for Solar Energy and Hydrogen Research in Stuttgart, Germany. The record-setting cell had an area of 0.5 cm^2 and was manufactured via a co-evaporation process. ZSW has long been a world record holder of CIGS since 2010. It has also agreed a joint partnership with Germany's Manz to move the new methods out of the laboratory and into the factory. Before 2010, the record is held by NREL for more than 10 years. Other world's leading institutions of CIGS includes Solibro in Germany, the subsidiary of Q-Cells that was bought by Hanergy, and Solar Frontier in Japan. For the mass production, Solar Frontier in Japan produced 900 MW in 2012, compared with 74 MW production capacity in 2010. Silibro, an affiliation of Q-Cells at the time, produced 140 MW compared with 70 MW capacity in 2011.

Nankai University held the China's record efficiency of CIGS until 2011. For small area (smaller or equal to 1cm2) CIGS solar cell, Nankai University improved its efficiency from 7.28% in 1995 to 8.83% % and 9.13% in 1999, then later to 12.1% in 2004, and finally to 15.35% and 15.6% in 2011. However, the Chinese record in 2011 was set not by Nankai University, but the group at CAS Shenzhen Institutes of Advanced Technology led by Dr. Xudong Xiao, which produced a 16.6% CIGS cell. The same group further increased it's the efficiency to 19.07% in 2013. By 2013, the difference between the record Chinese CIGS lab efficiency and the world record was only 1 percentage point, whereas it was more than 9 percentage points in 1995.

*Data collection and initial analysis conducted by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.

Exhibit 9. Perovskite World and Chinese Efficiency Records*

When the very first pervoskite solar cell efficiency was reported in 2006, its efficiency was only tested at 2.19%. It increased to 3.81% in 2008. However, it is only a matter of time before this technology caught on fire. Since the beginning of the 2010s, extremely rapid progress has been made as a result of is academic competition among the major research groups. Graetzel's group at Swiss Federal Institute of Technology (EPFL), Snaith's group at Oxford University, Seok's group at Korea Research Institute of Chemical Technology, Park's group at Sungkyunkwan University in Korea and Yang's group at University of California, Los Angeles (UCLA) all produced significant improvement to efficiency.

The world record efficiency was set to 6.5% in 2011 by a Park's research group. Further increase of the efficiency was made in 2012. A 12% efficient pervoskite cell was announced in 2012 as a result of collaboration between the Swiss and Korean scientists. In 2013, research groups from Korea, Switzerland, and Britain all produced new efficiency records, and by the end of 2013, the efficiency frontier was pushed to 16.2% by Dr. Seok of South Korea. In 2014, the UCLA group led by Chinese-American scholar Yang Yang updated the efficiency record to 19.3%.

China entered Perovskite research relatively late. The first perovsike solar cell efficiency was produced in Hong Kong University of Science and Technology (HKUST), and it was tested at 4.87% efficient in 2013. Since then, a leapfrogging happed to pervoskite research in China when multiple research groups enter the area and created competition among the innovation players (Section 3.3.3.2). As a result, Chinese record efficiency was updated 9 times by 8 different research groups in 16 months and eventually stood at 15.4% in April 2014.

* Data collection and initial analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.

Exhibit 10. Organic PV World and Chinese Efficiency Records*

Research on organic photovoltaic (OPV) materials and devices has flourished in recent years due to its potential to offer low-cost solar energy. The organic donor–acceptor heterojunction structure produced by Eastman Kodak Company in 1986 is considered as the foundation for all OPV devices. It produced a nearly 1% efficient OPV cell. The first bulk heterojunction structure of 1% efficientwas developed by Alan Heeger at UCSB in 1995. The performance of OPV devices, including the efficiency and stability, has since been steadily improving. There are many research groups working on OPV around the world. UCSB, Johannes Kepler University of Linz, Austria, Plextronics and Konarka Technology. and Solarmer in the U.S., and Siemens in Germany have all set world records. New materials and novel device architectures have been developed. In 2011, Mitsubishi Chemical announced that their small area single layer OPV cell reached 10.7% efficiency; it was the first time that an organic solar cell exceeds 10% lab efficiency. The world record efficiency improvement was stagnant since then until 2015, when researchers from North Carolina State University in the U.S. and Hong Kong University of Science and Technology produced an 11.5% efficient OPV cell.

Chinese researchers started OPV researcher not too long after the world's leading institutes began to move into this technology space. Professor Li's group at CAS Institute of Chemistry and Dr. Cao's group at South China university of Technology (SCUT) produced the majority of the efficiency records in China. The efficiency trajectory of OPV cells follows closely of the world record efficiency. In 2007, the world record was 5.5%, produced at UCSB, while the Chinese record produced by SCUT was just 0.1 percentage point lower. During the time period between 2011 and 2015, where the world record remained static, new Chinese records kept being produced. Li's group at CAS Institute of Chemistry announced a Chinese record of 7.59% in August 2011, and one month later, Cao's group at SCUT improved the efficiency to 8.37%. The latter group has since produced two higher efficiency cells; one tested at 9.20% efficient in 2012, and the other one tested at 9.28% efficient in 2014.

* Data collection and initial analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.

Exhibit 11. CdTe World and Chinese Efficiency Records*

Just like Sanyo holds the exclusive technology of HIT, First Solar takes the dominant position of CdTe. The company started the research of CdTe as early as 1990s. It launched production of commercial products in 2002. After crushed the efficiency mark for CdTe with a world-record 20.4% in 2014, First Solar set the new record of 21.5% in February 2015. FirstSolar's full fleet average conversion efficiency was 14.4 percent and the lead line at First Solar was averaging 14.8 percent in Q4 2014. In the early days, First Solar collaborated with many universities and research institutions such as University of Toledo, Colorado School of Mines and the University of South Florida. However, the collaboration is suspended when the company started to develop Vapor Transport deposition (VTD) technology at the beginning of 2000s. Currently, First Solar is the exclusive owner of high efficiency CdTe technology. In comparison with FirstSolar's VTD technology of high temperature, other leading research institutions such University of Toledo develops a 14.5%-efficient CdTe solar cell by magnetron sputtering at low temperature.

Sichuan University is among the first few universities that worked on CdTe solar cells in China. During the 9^{th} FYP (1995-2000), it achieved an efficiency of 13.38% in 2003. Its 300 KW pilot production line can produce 40cm x 30cm solar modules at an efficiency of 8.25%. CAS Institute of Electrical Engineering succeeded in producing a $0.02cm^2$ CdTe cell at 14.4% efficient in 2014. Shanghai Center for Photovoltaic, together with Professor Deliang Wang from China University of Science and Technology, managed to produce a CdTe cell of nearly 14% efficient on a $0.07cm^2$ glass substrate in 2012 and 14.6% efficient of 0.25 cm^2 using chemical bath deposition method.

* Data collection and initial analysis conducted as part of the Stanford China Project by Zhao (Joy) Zhu, a member of the Stanford University China Project research team.

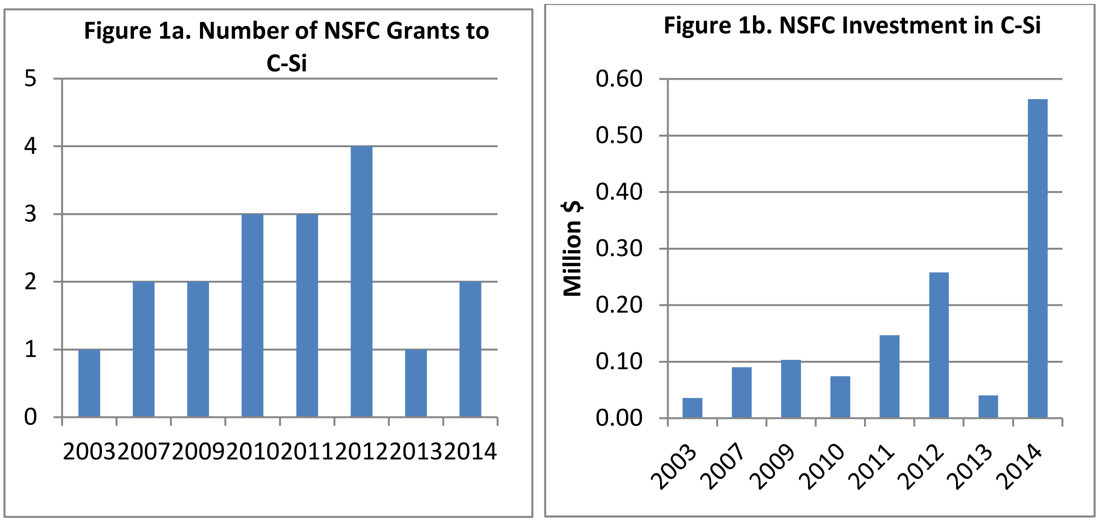


Figure B.1. NSFC Investment in C-Si*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

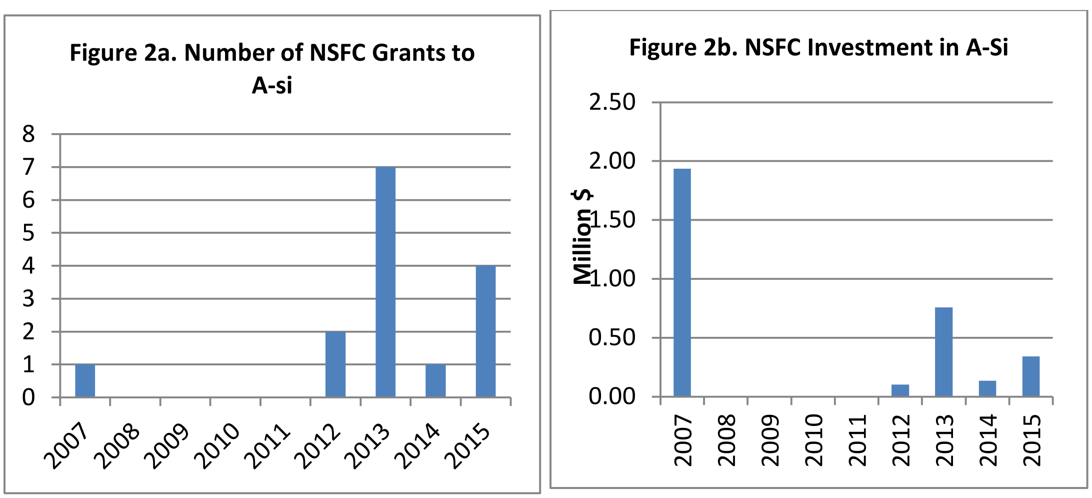


Figure B.2. NSFC Investment in a-Si

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

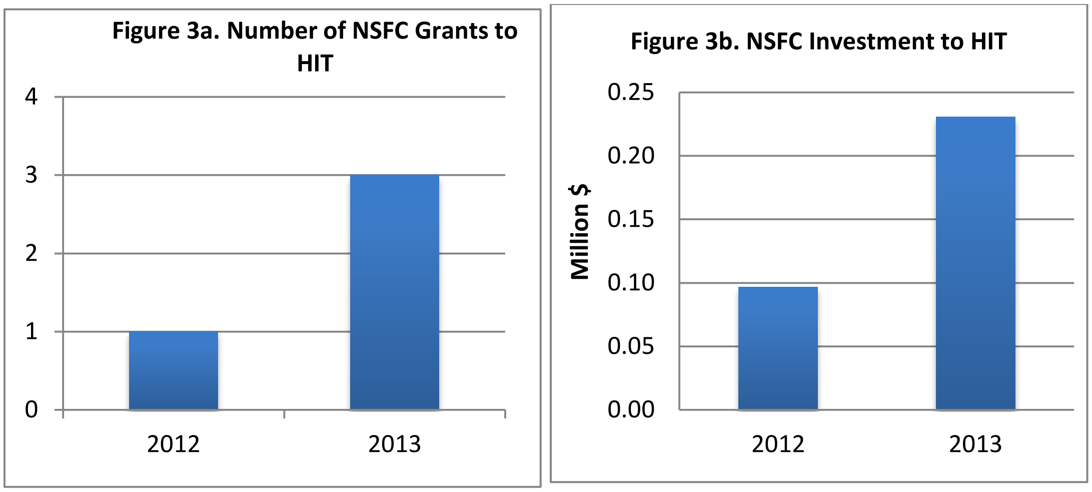


Figure B.3. NSFC's Investment in HIT*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

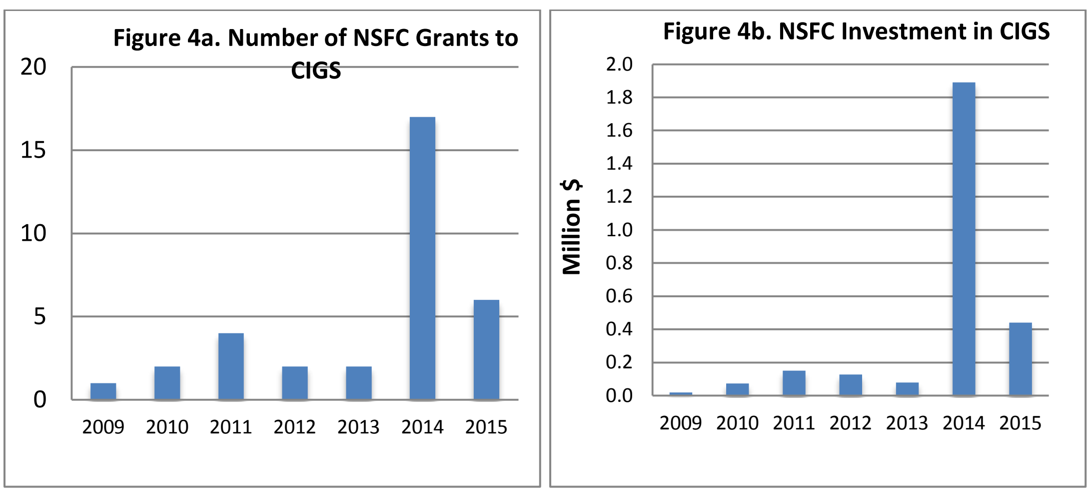
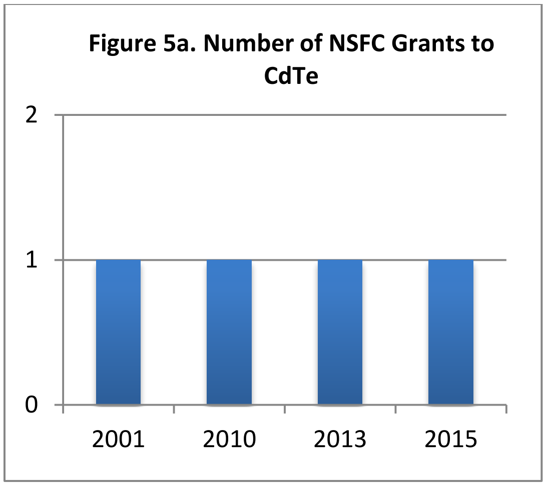


Figure B.4. NSFC Investment in CIGS*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.



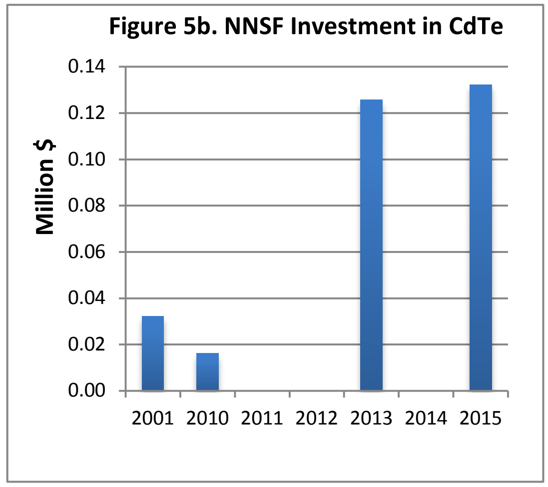
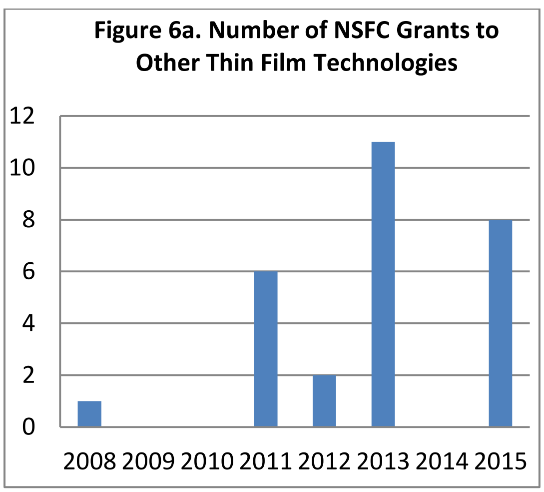


Figure B.5. NSFC Investment in CdTe*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.



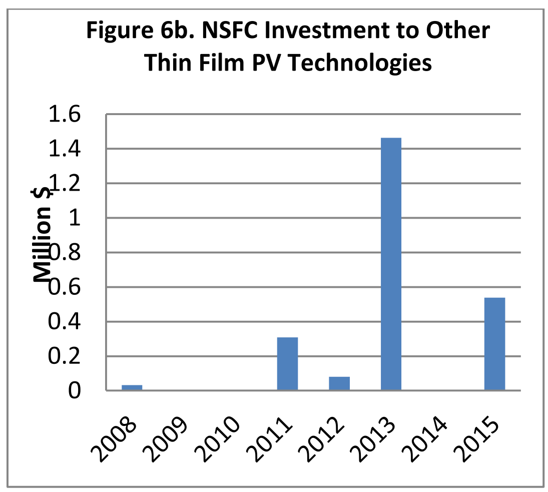


Figure B.6. NSFC Investment in Other Thin Film Technologies*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

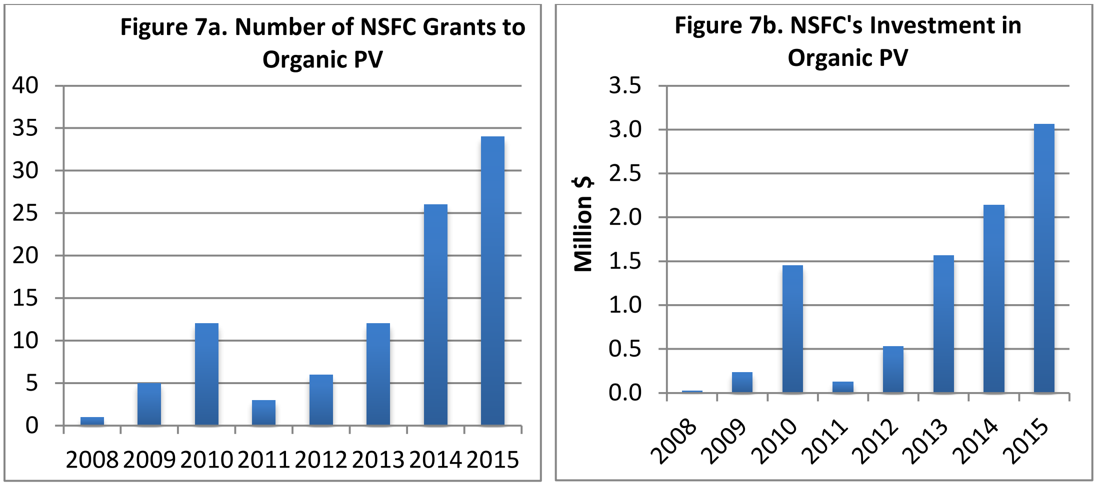


Figure B.7. NSFC’s Investment in Organic PV*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

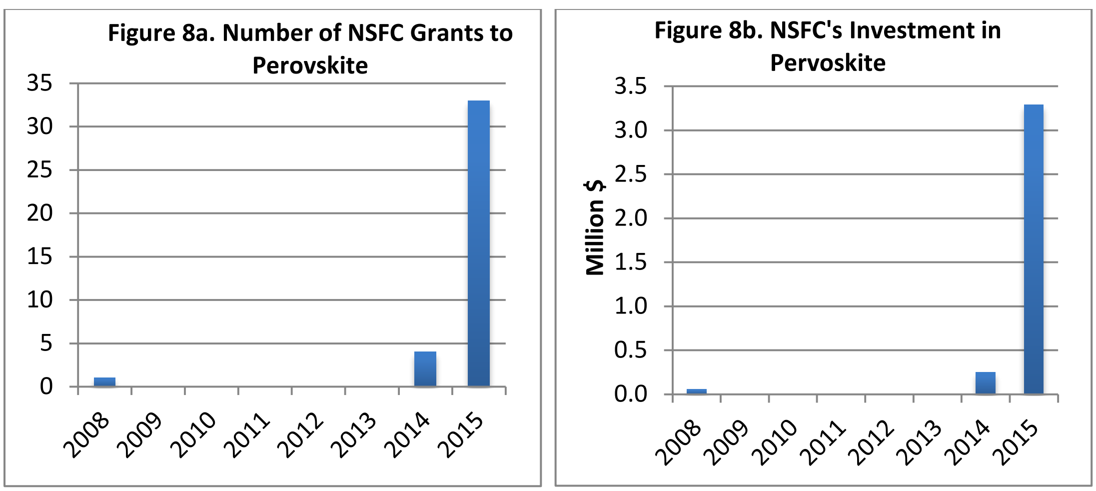


Figure B.8. NSFC’s Investment in Perovskite*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

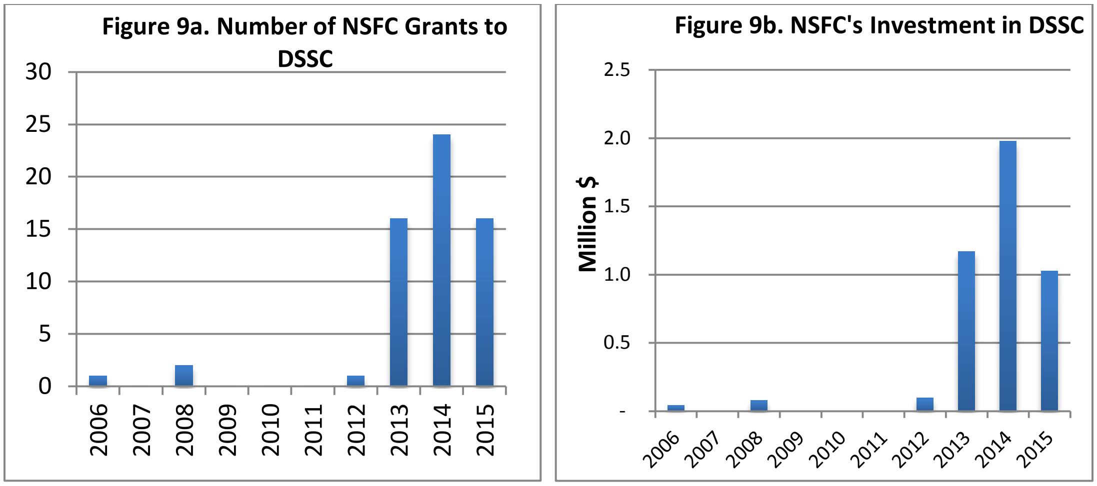


Figure B.9. NSFC's Investment in DSSC*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

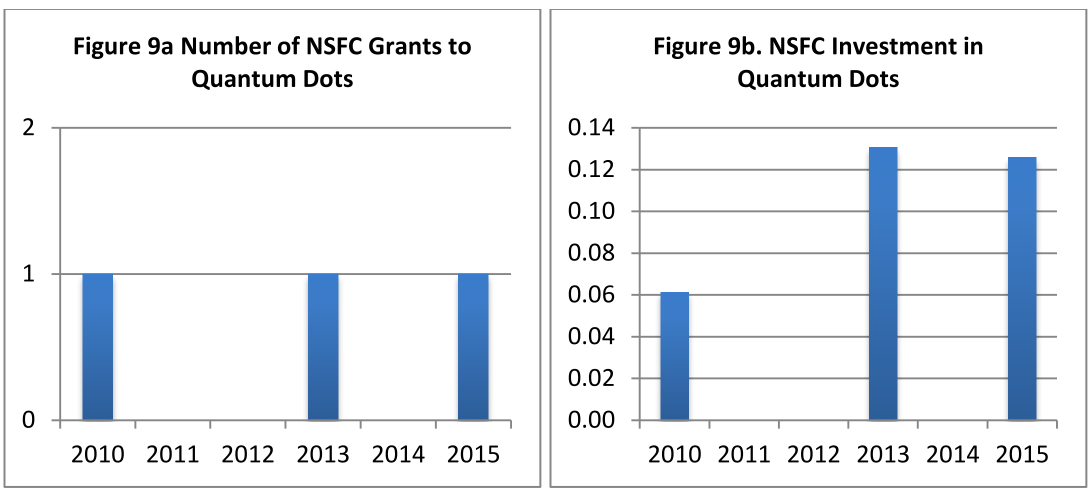


Figure B.10. NSFC's Investment in Quantum Dots*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

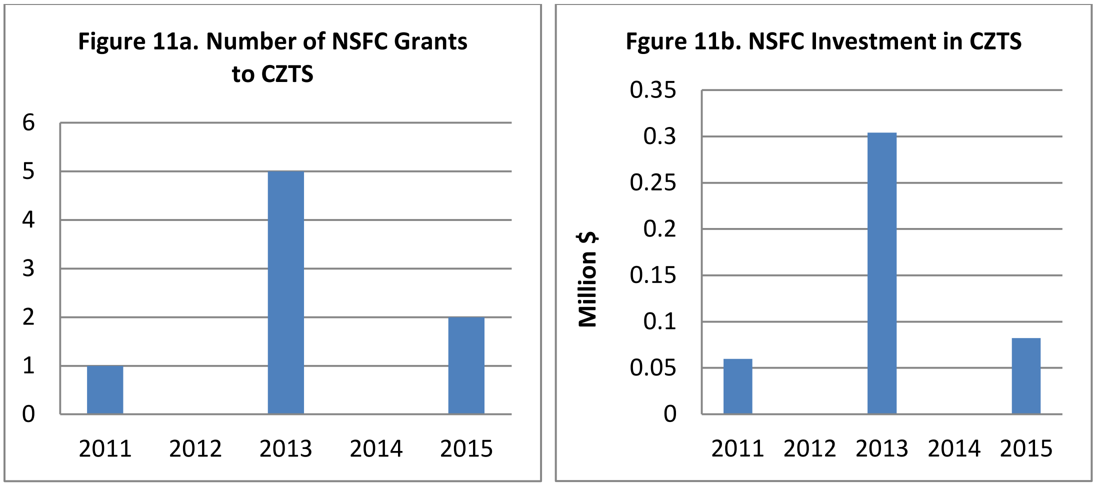


Figure B.11. NSFC's Investment inCZTS*

* Note: Data collected as part of the Stanford China Project. Analysis in the figures is done as part of the Stanford China project by the author.

Table B.2 Top Five Patent Holders of Category 1 solar PV technologies

	China			Foreign		
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
Mono-Si						
1	Trina	13	Company	Sanyo	15	Company
2	Zhejiang university	11	Academic	Mistubishi	11	Company
3	Canadian Solar (Suzhou)	8	Company	Shin-Etsu Chemical	11	Company
4	Canadian Solar (Changshu)	5	Company	Kaneka	8	Company
5	Beijing Solar Technology	5	Company	Sharp	7	Company
Top 5 entities as a % of total number of patents			15.8%	Top 5 entities as a % of total patents		21.7%
Total		265		Total	240	
Poly-Si						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Nankai University	6	Company	Sharp	5	Company
2	Xiamen Univeristy	6	Academic	IBM	4	Company
3	Zhejiang University	6	Company	Industrial Technology Research Institute	3	Company
4	Hunan University	6	Company	BT photonic	2	Company
5	Trina	6	Company	Canon	2	Company
Top 5 entities as a % of total number of patents			16.6%	Top 5 entities as a % of total patents		27.6%
Total		181		Total	58	
PERC						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Trina Solar	7	Company	REC	4	Company
2	Canadian Solar (Suzhou)	5	Company	LG	3	Company

Table B.2 Continued

Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
3	Canadian Solar	5	Company	Georgia tech Research Corporation	2	Company
4	Zhongshan University	4	Academic	Robert Bosch GmbH	1	Company
5	CAS(Electrica)	3	Academic	Mosel Vitelic Inc.	1	Company
Top 5 entities as a % of total number of patents			48.0%	Top 5 entities as a % of total patents		73.3%
Total		50		Total	15	
HIT						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Nankai University	7	Academic	Applied Material	5	Company
2	CAS (Semiconductor)	5	Academic	General Electric	4	Company
3	CAS (Electric)	4	Academic	Sanyo	3	Company
4	Linuo Solar Power	4	Company	Princeton University	3	Academic
5	Trina	4	Company	Solyndra	3	Company
Top 5 entities as a % of total number of patents				Top 5 entities as a % of total patents		26.1%
Total				Total	92	
CIGS						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	CAS (Shenzhen)	8	Academic	Industrial Technology Research Institute	13	Company
2	China Electronics Technology Group Corporation	7	Academic	DuPont	5	Company
3	Tsinghua University	6	Academic	Soribulo Research Company	4	Company
4	CAS (Shanghai)	6	Academic	Showa Shell Sekiyu	3	Company

Table B.2 Continued

Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
5	Wuxi Solar PV Agricultura l Cultivation Plantations	5	Company	Solyndra	3	Company
Top 5 entities as a % of total number of patents			24.6%	Top 5 entities as a % of total patents		42.4%
Total		130		Total	66	
CdTe						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	CAS (Physics)	28	Academic	Industrial Technology Research Institute	10	Academic
2	Baoding Tianwei Group Co	6	Company	DuPont	5	Company
3	Sichuan University	6	Academic	BASF	3	Company
4	Shanghai Solar Battery R&D Center	4	Academic	First Solar	3	Company
5	CAS (Shanghai)	4	Academic	Solar System and Equipment	2	Company
Top 5 entities as a % of total number of patents			39.3%	Top 5 entities as a % of total patents		31.5%
Total		122		Total	73	
a-Si						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Nankai University	16	Academic	Sanyo	6	Company
2	Yi Li	16	Individual	Applied Materials	3	Company
3	CAS (Semi-conductor)	6	Academic	Sony	3	Company
4	Donghsu Group	4	Company	LG	2	Company

Table B.2 Continued

Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
5	Harbin Industrial University	4	Academic	Mistubishi	2	Company
Top 5 entities as a % of total number of patents			31.5%	Top 5 entities as a % of total patents		38.1%
Total		146		Total	42	
Perovskite						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Tongji Univeristy	3	Academic	Samsung	3	Company
2	Zhejiang University	3	Academic	BASF	1	Company
3	BYD Company	2	Company	Nela Corp.	1	Company
4	Shanghai Jiaotong University	1	Academic	Panasonic	1	Company
5	CAS (Shanghai)	1	Academic	Panasonic	1	Company
Top 5 entities as a % of total number of patents			71.4%	Top 5 entities as a % of total patents		46.7%
Total		14		Total	15	
MWT						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Tianwei New Energy	1	Company	LG	1	Company
2	Giga Solar	1	Company	Hyundai Heavy Industries	1	Company
3	SRPV High-Tech Co	1	Company			
4	JA Solar	1	Company			
5	Yingli	1	Company			
Top 5 entities as a % of total number of patents			100%	Top 5 entities as a % of total patents		100%
Total		5		Total	2	
GaAs						

Table B.2 Continued

Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	CAS (Suzhou)	11	Academic	Australian Numerical Controls and Automation	11	Company
2	CAS (semi-conductor)	7	Academic	Industrial Technology Research Institute	6	Academic
3	Sanan Optoelectronics Co	3	Company	IBM	4	Company
4	Hongfujin Industry	3	Company	Nakata TsueYu	3	Individual
5	Dongnan University	3	Academic	Kyo Semi Co	2	Company
Top 5 entities as a % of total number of patents			30%	Top 5 entities as a % of total patents		36.1%
Total		9		Total	72	
Multi-junction						
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Nankai University	16	A	Australian Numerical Controls and Automation	9	Company
2	CAS (Nano-tech)	8	A	DuPont	3	Academic
3	San'an Optoelectrics	4	C	TSMC	2	Company
4	Tianjin University of Sci&Tech	3	A	IBM	2	Individual
5	Huazhong technology University	3	A	Applied Materials	2	Company
Top 5 entities as a % of total number of patents			28.3%	Top 5 entities as a % of total patents		41.9%
Total		120		Total	43	

Note:
Data collection facilitated by Evalueserve http://www.evalueserve.com/
Data collection and analysis done as part of Stanford China Project.

Table B.3 Top Five Patent Holders of Category 2 solar PV technologies

	China			Foreign		
Ranking	Entity	# of Patent	Type	Entity	# of Patent	Type
	Organic					
1	CAS (Chemistry)	15	Academic	Metal Industries Research and Development Center	9	Academic
2	CAS (Physics)	13	Academic	Samsung	8	Company
3	CAS (Applied Chemistry)	13	Academic	Fujikura	7	Company
4	Rainbow Corp.	11	Company	Sony	7	Company
5	Tsinghua University	11	Academic	Gracel Display Inc.	7	Company
Top 5 entities as a % of total number of patents			20.3%	Top 5 entities as a % of total patents		38.8%
Total		310		Total	98	
	DSSC					
Ranking	Entity	# of Patent	Type	Entity	# of Patent	Type
1	Nankai University	6	Company	Sharp	5	Company
2	Xiamen University	6	Academic	IBM	4	Company
3	Zhejiang University	6	Company	Industrial Technology Research Institute	3	Company
4	Hunan University	6	Company	BT photonic	2	Company
5	Trina	6	Company	Canon	2	Company
Top 5 entities as a % of total number of patents			16.6%	Top 5 entities as a % of total patents		27.6%
Total		181		Total	58	
	Quantum Dot					
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Wuhan University	8	Academic	Princeton University	7	Academic

Table B.3 Continued

Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
2	Fudan University	7	Academic	Michigan University	5	Academic
3	Huazhong University of Science and Technology	6	Academic	AU Optronics Corporation	4	Company
4	Xi'an Jiaotong University	6	Academic	Nichiya	4	Company
5	CAS(Physics)	5	Academic	Industrial Technology Research Institute	3	Academic
Top 5 entities as a % of total number of patents			18.1%	Top 5 entities as a % of total patents		50.0%
Total		177		Total	46	
	CTZS					
Ranking	Entity	# of Patent	Type	Name	# of Patent	Type
1	Donghua University	4	Academic	Korea Energy Technology Research Center	1	Company
2	Guilin University of Sci & Tech	3	Academic			
3	Shanghai Jiaotong Unviersity	2	Academic			
4	CAS(physics)	2	Academic			
5	Hefei Industrial University	2	Academic			
Top 5 entities as a % of total number of patents			46.4%	Top 5 entities as a % of total patents		100%
Total		28		Total	1	

Note:
Data collection facilitated by Evalueserve http://www.evalueserve.com/
Data collection and analysis done as part of Stanford University China Project.

Table B.4 Top Five Patent Holders of Category 3 solar PV technologies

	China			Foreign		
Ranking	Entity	# of Patent	Type	Entity	# of Patent	Type
IBC						
1	CAS (Electric)	2	Company	AZUR SPACE Solar Power	2	Company
2	Trina	2	Company	Solibro	2	Company
3	Shanghai Jiaotong University	1	Academic	Feibu Corp	2	Company
4	Changzhou University	1	Academic	SLIa	2	Company
5	JA Solar	1	Company	Fraunhofer	1	Academic
Top 5 entities as a percentage of total number of patents			87.5%	Top 5 entities as a percentage of total number of patents		32.1%

Note:
Data collection facilitated by Evalueserve http://www.evalueserve.com/
Data collection and analysis done as part of Stanford University China Project.

APPENDIX C

SUPPLEMENTARY MATERIALS TO CHAPTER 4

Exhibit 1: Delicacy Management at GCL Poly

At GCL Poly, the global leading Chinese silicon and wafer producers, delicacy management is implemented at both the executive level and at the grass root level[79]. At the company headquarter, there is a working group in the management center dedicated to study delicacy management and its strategic implications. The company also runs an organizational-wide campaign to promote the concept and the practices among its employees. The working group from time to time conducts studies to assess factories' production performance and identify areas for improvement. They focus their attention on optimizing three levels of operations in their factories. At the most basic level, they take a page from Taylor's scientific management approach by studying the movement of workers and how they operate machines and pass materials from one stage to the next. Step two, they apply information learned from step one to design across-procedural practices to optimize the efficiency of the entire production line. Step three, if the most efficient practice cannot be accommodated by the current production line, they will redesign the production line or even the entire workshop in order to implement the more efficient operation.

Speaking of efficiency, it is a multi-faucet concept under delicacy management. It requires optimization on multiple fronts, including reducing time, material waste and solar cell breakage rate; increasing yields; shortening transition time and down time; reducing onsite inventory; increasing the level of automation with reasonable human control; and reducing the number of sub-par products.

The ultimate goal is to control cost and increase final product quality. This approach has allowed GCL Poly to achieve a new level of cost-competitiveness in their

[79] Tour ID #3

latest poly-silicon production plant. When it was first built, it followed the standardized modular workshop design, meaning arranging the production process one module after another. However, the manager quickly found that the cost was higher than they expected. They applied the delicacy management approach to examine the production process and discovered that for the particular product produced in that factory, the modular style production line design prolongs the material transporting time between modules, which led to inefficiency. In response, they decided to redesign the workshop and the production line to streamline the production process to fit the product. The end result was a faster production processes requiring a smaller number of processes, which the company time, money, and labor.

Besides the top-down approach, a grass root approach was also put in place through which about ways to improve the efficiency of individual processes as well the entire system proposals can be submitted to the company management center from managers and production line workers. If they are found to be viable, then they will be implemented.

Exhibit 2: History of Pragmatism in China

Pragmatism was first introduced to China by no other than its most famous champion, John Dewey. Dewey traveled to China in 1919 and stayed for 2 years to teach and advocate pragmatism. His Chinese disciple, Hu Shi, also became an influential figure and carried Dewey's torch after he returned to the U.S. Pragmatism was well accepted in China in the first half of the 20th century until the establishment of the People's Republic of China in 1949 (Tan, 2004). Under the first 30 years of the Chinese Communist Party rule, pragmatism was criticize for many reasons including its opposition to the dictation of ideology and the of instrumentalism component of it. However, it was revived after the implementation of the "open door" policy in 1978 and the market-base economic reform that came right after that.

Famously said by former Chairman and the architect of the Chinese economic reform Deng Xiaoping, "Practice is the sole criterion of truth." The whole economic reform that broke ties with planned economy and adopted principles of market economy was essentially pragmatic because if it were to follow the communist ideology, none of the market-based solutions would be sanctioned since they were inherently capitalistic, the very ideology that communism decries. Nevertheless, by embracing pragmatism, Deng and his successors bypassed the controversial ideological debates, and proposed a new framework, which was to roll up the sleeves and do things, and then let the results decide the legitimacy of the action, rather than leaving it to ideological criteria. From a TIS perspective, this new framework is inherent entrepreneurial because it took the risks with regard to a new approach to run a country's economy and it experimented with it and eventually reduced the uncertainty of such approaches and legitimized its existence (***entrepreneurial experimentation***). In fact, the economic reform at its initial stage was made of many local-scale experiments. They tested concepts such as allowing temporary collective or private ownership of farmland, private ownership of enterprises, free-market based pricing system, etc, all of which would deemed as risky and controversial at least if not scandalous under a rigid communism regime. But because of the pragmatic framework Deng promoted, the experiments were largely judged on their outcome rather than their ideology camp. Successful small scale local experiments were later rolled out to a larger area, and eventually became nation-wide practice.

Contrary to the conventional wisdom, China scholars have long noticed that when it comes to policy design, modern China is surprisingly decentralized and full of experimental and risk-taking spirit (Bardhan, 2002; Heilmann, 2008; Jin, Qian, & Weingast, 2005) rather than being a tightly central-controlled economy. Experiments, or in a TIS sense, ***entrepreneurial experimentations,*** are at the front and centered of many new economic policy designs. Besides the above-mentioned experiments with property ownership and market-based pricing system, one recent and energy-related policy program is also a good example of experiment-based pragmatism. In designing its greenhouse gas regulation, China created 5 pilot cities and 2 pilot provinces since 2011 to test different carbon emission trading schemes. The cap-and-trade systems implemented by different cities and provinces vary from how they treat price floor, price ceiling, credit banking and borrowing, industry coverage, etc. The idea is to explore different policy design and understand their merits and drawbacks. Information collected at the municipal and provincial level directly informed the final design of the national cap-and-trade system, which was announced in September 2015.

Table C.1 Key Subsidy Types Addressed in US-China Solar Trade Cases

Type	Details
Investment Subsidies/Grants	
Golden Sun Demonstration Program to Trina	2009; provided one-time assistance over the course of its 2-yr term
Discovered Grants to Suntech & Trina	R&D Grant
Sub-Central Government Subsidies for Development of "Famous Brands" & "China World Top Brands" Suntech	Grant provided by Wuxi City contingent on export performance (i.e. application required disclosure of export ratios & compliance with international standards)
Special Energy Fund to Suntech	Provided in Shandong
Fund for Outward Expansion of Industries	Provided in Guangdong
Tax Incentives	
"Two Free, Three Half" Program for Foreign-Invested Enterprises (FIEs) to Luoyang Suntech & Zhenjiang Huantai (cross-owned affiliates of Suntech)	Terminated in Jan 2008, but preferential tax rate grandfathered-in for many (tax-exempted in first 2 years of profitability & assessed 50% of standard income tax rate for next 3 years)
Preferential Tax Program for High or New-Tech Enterprises (HNTEs) to Suntech & Trina	Established Jan 2008; Recognized HNTEs eligible for reduced income tax of 15% (down from standard 25%)
Enterprise Income Tax Law, R&D Program[80] to Suntech & Trina	Tax reduction constitutes a financial contribution in the form of government revenue foregone & a benefit in the amount of tax savings
Import Tariff & VAT Exemptions for Use of Imported Equipment to Trina, Suntech, Luoyang Suntech, Shanghai Suntech, Zhenjiang Huantai, Suzhou Kuttler	
VAT Rebates on FIE Purchases of Chinese-Made Equipment to Trina	Deemed specific, as VAT rebates are contingent on use of domestic over foreign equipment

[80] Solar I Countervailing Duties (CVD) Final Decision Memorandum (http://enforcement.trade.gov/frn/summary/PRC/2012-25564-1.pdf), page 17. "Allows enterprises tax deductions of research expenditures incurred in the development of new technologies, products, and processes. If eligible research expenditures do not "form part of the intangible assets value," an additional 50% deduction from taxable income may be taken on top of the actual accrual amount. Where these expenditures form the value of certain intangible assets, the expenditures may be amortized based on 150% of the intangible assets costs."

Table C.1 Continued

Type	Details
Income Tax Reductions for Export-Oriented FIEs	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.
Income Tax Benefits for FIEs Based on Geographic Location	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.
Local Income Tax Exemption & Reduction Programs for "Productive" FIEs	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.
Tax Refunds for Reinvestment of FIE Profits in Export-Oriented Enterprises	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.
Preferential Lending	
Export Seller's Credits	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.
Export Buyer's Credits Suntech & Trina	Ex-Im Bank loans provided at preferential rates for purchase of exported goods from China
Input Subsidies	
Provision of Polysilicon LTAR to Suntech & Trina	(Deemed specific to cell producers)
Provision of Land for LTAR to Suntech & Trina	(Constitutes a financial contribution from an authority in the form of goods/services)
Provision of Aluminum for Less Than Adequate Remuneration (LTAR)	No deeded as countervailable because this was not an act that target the solar PV energy industry specifically.

Source: Solar I Countervailing Duties (CVD) Final Decision Memorandum (http://enforcement.trade.gov/frn/summary/PRC/2012-25564-1.pdf); Solar II CVD Final Decision Memorandum (http://enforcement.trade.gov/frn/summary/prc/2014-30071-1.pdf).

Note: Information collection and table compilation were conducted as part of the Stanford China Project and were led by Cait Pollock.

Table C.2. Anecdotal Examples of Government Solar Subsidies

Subsidy Type	Recipient	Provider/ Source	Timeframe	Details
Investment Subsidies/Grants				
Project development funds	CSI	Suzhou New District government	Q2 2009	US$1.09M (RMB 7.5M) provided to match central RE stimulus funds, for CSI to develop projects locally[81]
R&D grants	LDK	Central government	Q4 2012	US$419,000[82]
R&D grants	LDK	Central government	Q1 2013	US$177,000[83]
R&D grant	PV producers in Jiaxing	Jiaxing municipal government		R&D grants from local government for local PV manufacturers[84]
R&D grant	LDK	Central government	Q4 2012	US$419,000[85]
R&D grant	LDK	Central government	Q1 2013	US$177,000[86]
R&D grant	Sunergy PST	MOST	2013	863 grant of US$4.7M (RMB 30M) to mass-produce PERC cells (with expectation that PST would self-invest 3x more[87]
Tax Incentives				
Revenue tax exemptions	Suntech	Central government	Undisclosed	Granted for 5 years following bankruptcy/ restructuring[88]
Local tax reduction	PV producers in Wuxi	Wuxi municipal government	Unknown	Local industrial tax reduction for companies with large revenues.[89]
Input Subsidies				

[81] Solar Daily article; May 4, 2009: http://www.solardaily.com/reports/Canadian_Solar_Announces_Funding_Agreement_With_City_of_Suzhou_999.html.
[82] LDK Q4 2012 earnings call (cited by BNEF).
[83] LDK Q1 2013 earnings call (cited by BNEF).
[84] Interviewee # 81, #82.
[85] LDK Q4 2012 earnings call (cited by BNEF).
[86] LDK Q1 2013 earnings call (cited by BNEF).
[87] Interviewee #102
[88] "Creditors Dispute Details as Suntech Finds Buyer," BNEF (China Solar Analyst Reaction); November 19, 2013: https://www.bnef.com/Insight/8856.
[89] Interviewee # 91

Table C.2 Continued

Subsidy Type	Recipient	Provider/ Source	Timeframe	Details
Secure infrastructure	LDK	Misc local/ provincial governments	2005/2006 onward	Free/cheap land & electricity grid[90]
Low electricity prices	DAQO	Shihezi municipal government	Q1 2014	Exclusive provincial rates through 2020[91]
	LDK	Xinyu municipal government	misc	Cheaper rate approved by local government[92]
Equipment purchase	Local PV manufacturer	Wuxi municipal government	Unknown	Government co-pay with companies for production upgrade[93]
Preferential Lending				
Bank loan guarantees	LDK	Xinyu municipal government	2005/2006	US$31.4M (RMB 200M) in funding & bank loans provided at company's inception[94]
Infrastructure / Social Welfare Contributions				
Social welfare contribution	Local PV manufacturer	Wuxi municipal government	Unknown	Local government chip in for companies' social security and pension funds. [95]
Expert recruitment package	Recruited scientists and entrepreneurs	Wuxi municipal government	Unknown	Recruitment packages including an automobile, an apartment, and a research lab, provided for free or heavily subsidized by the local government [96]
Factory plants	PV manufacturers	Wuxi government and industrial park administration	Unknown	Pre-built standardized factory floor[97]

[90] NBD article; June 22, 2012: http://www.nbd.com.cn/articles/2012-06-22/662422.html.
[91] DAQO Q1 2014 earnings call (cited by BNEF).
[92] Imeigu article; May 26, 2013: http://news.imeigu.com/a/1369576370859.html.
[93] Interviewee # 91
[94] Imeigu article; May 26, 2013: http://news.imeigu.com/a/1369576370859.html.
[95] Interviewee # 91
[96] Interviewee # 91
[97] Interviewee # 91

Table C.2 Continued

Subsidy Type	Recipient	Provider/ Source	Timeframe	Details
Public transit	Employees at local industrial park/PV production plants	Wuxi municipal government	Unknown	Public transit system for people who work at local industrial parks including employees of PV companies, provided for free or heavily subsidized by local government[98]
International school	International employees working at Trina Solar Industrial Park	Changzhou municipal government and Trina Solar	Unknown	International school located in Trina Solar Industrial Park, subsidized by local government and Trina Solar[99]

Notes: Note: Information collection was conducted as part of the Stanford China Project.

Table initially compiled as part of the Stanford China Project by Cait Pollock, and further appended and analyzed by the author of this dissertation.

[98] Interviewee # 91

[99] Tour at Trina Solar Industrial Park, on August 28, 2014.

Exhibit 3. PV Deployment Program in China before 2013

The Solar Roofs Program was created by MOF and Ministry of Housing and Urban-Rural Development (MOHURD) in 2009 to provide capital subsidies for BIPV and rooftop PV systems at ¥ 20/Watt ($ 2.9/Watt) and ¥15/Watt ($ 2.2/Watt) level, respectively. The subsidy levels were later downgraded to ¥ 17/Watt ($ 2.5/Watt) and ¥ 13/Watt ($ 1.9/Watt) to reflect the declining PV module price. In order to qualify for the subsidies, a PV project has to have a minimum capacity of 50kW and the PV modules have to meet the minimum efficiency floors: 16%, 14% and 6% for monocystalline PVs, polysilicon PVs, and thin-films, respectively.

The Golden Sun Demonstration Program was initially set up to subsidize the total investment of a solar project. It was established in 2009 and offered 50% subsidy to grid-connected rooftop PV, BIPV, and ground-mounted systems and its associated transmission and grid connection costs, and 70% subsidies to off-grid solar PV projects in remote areas. In a revision in 2011, the program changed its subsidy mechanism from a fixed percentage of total project investment to ¥ 9/W ($1.3/W) subsidy for projects using crystalline modules and ¥ 8/W (1.2/W) for projects using thin-film modules. The subsidies were further adjusted downward to ¥ 7/W ($1/W) for all PV module types in a 2012 revision, reflecting the fast declining module price. By the time the two programs ended in 2013, 3.38GW of distributed solar had been installed as a result of these two programs (Chinese Academia of Sciences, 2014).

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APPENDIX D

SUPPLEMENTARY MATERIALS TO CHAPTER 5

Table D.1 Chinese Solar PV Suppliers in 2013*

<table>
<tr><th colspan="3">Company Directory</th><th>Number of Chinese Manufacturers</th></tr>
<tr><td rowspan="31">Solar Ingot / Wafer / Cell / Panel Equipment Manufacturers</td><td rowspan="8">Crystalline Panel Production Equipment</td><td>Turn-Key System</td><td>20</td></tr>
<tr><td>Inspecting/Testing</td><td>111</td></tr>
<tr><td>Cleaning</td><td>28</td></tr>
<tr><td>Tabbing/Stringing</td><td>53</td></tr>
<tr><td>Laminating</td><td>58</td></tr>
<tr><td>Cutting/Scribing</td><td>35</td></tr>
<tr><td>Framing</td><td>50</td></tr>
<tr><td>Other</td><td>71</td></tr>
<tr><td rowspan="8">Cell Production Equipment</td><td>Turn-Key System</td><td>3</td></tr>
<tr><td>Etching</td><td>27</td></tr>
<tr><td>Diffusion</td><td>22</td></tr>
<tr><td>Coating/Deposition</td><td>23</td></tr>
<tr><td>Screen Printing</td><td>12</td></tr>
<tr><td>Other Furnaces</td><td>27</td></tr>
<tr><td>Inspecting/Testing</td><td>60</td></tr>
<tr><td>Other</td><td>12</td></tr>
<tr><td rowspan="6">Wafer Production Equipment</td><td>Turn-Key System</td><td>0</td></tr>
<tr><td>Cutting</td><td>24</td></tr>
<tr><td>Cleaning</td><td>62</td></tr>
<tr><td>Inspecting/Testing</td><td>23</td></tr>
<tr><td>Polishing & Grinding</td><td>4</td></tr>
<tr><td>Other</td><td>33</td></tr>
<tr><td rowspan="5">Ingot / Block Production Equipment</td><td>Turn-Key System</td><td>0</td></tr>
<tr><td>Crystalline Ingot Growing</td><td>34</td></tr>
<tr><td>Inspecting/Testing</td><td>9</td></tr>
<tr><td>Cutting & Grinding</td><td>18</td></tr>
<tr><td>Other</td><td>1</td></tr>
<tr><td rowspan="2">Thin-Film Panel Production</td><td>Turn-Key System</td><td>4</td></tr>
<tr><td>Inspecting</td><td>16</td></tr>
</table>

Company Directory			Number of Chinese Manufacturers
	Equipment	Coating/Deposition	10
		Cutting/Scribing	16
		Cleaning	3
		Etching	5
Solar Components		Inverter	343
		Charge Controller	185
		Battery	170
		Converter	9
		Monitoring System	42
		Mounting System	152
		Tracker	48
		PV Panel/Array Outdoor Tester	18
		Transformer	28
Solar Materials	Crystalline Panel Process	Cell	161
		Ribbon	54
		Glass	91
		Encapsulant	50
		Backsheet	56
		Cable	64
		Junction Box	107
		Connector	100
		Frame	62
		Other	67
	Cell Process	Wafer	132
		Metallization Paste	40
		Screen	24
		Ammonia	16
		Isopropyl Alcohol	14
		Phosphrous-oxychloride	8
		Silane	15
		Acids	18
		Hydroxide	14
	Wafer Process	Ingot/Block	109
		Saw Band	10

Company Directory			Number of Chinese Manufacturers
		Slurry	123
		Saw Wire	26
		Ingot mounting adhesives	10
		Acids	27
	Ingot Process	Polysillicon	52
		Recycled Material	17
		Crucible	105
		Insulation felt	38
		Seed Crystal	2
	Thin Film Panel Process	Glass	91
		Cable	64
		Junction Box	109
		Connector	100
		Frame	62
		TCO Material	0
		Sputtering Target	55
		Encapsulant	49
		Backsheet	26
		Cadmium Sulfide	6
		Boron	9
		Copper	17
		Gallium	18
		Germanium	21
		Indium	28
		Molybdenum	40
		Tellurium	18
		Tin	17
		Selenium	4
		Oxides	5
		Phosphrous-oxychloride	8
		Silane	6
		Alumina	11
Solar Panels	Crystalline		531
	Thin-Film	Amorphous	37

Company Directory			Number of Chinese Manufacturers
		CIS Family	8
		CdTe	2
	Other	CPV	9
		Innovative Panel Design	15
		Third Generation	2

Source: Table compiled using ENF database http://www.enfsolar.com/directory/equipment

Data collected and analyzed as part of the Stanford China Solar Project.

Data collected as part of the Stanford China Project by Jingfan Wang, a member of the Stanford China Solar Project, and analyzed by the author of this dissertation.

Strength of China’s supply chain that remains strong

Figure D. 1. Global Top 10 PV Glass Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

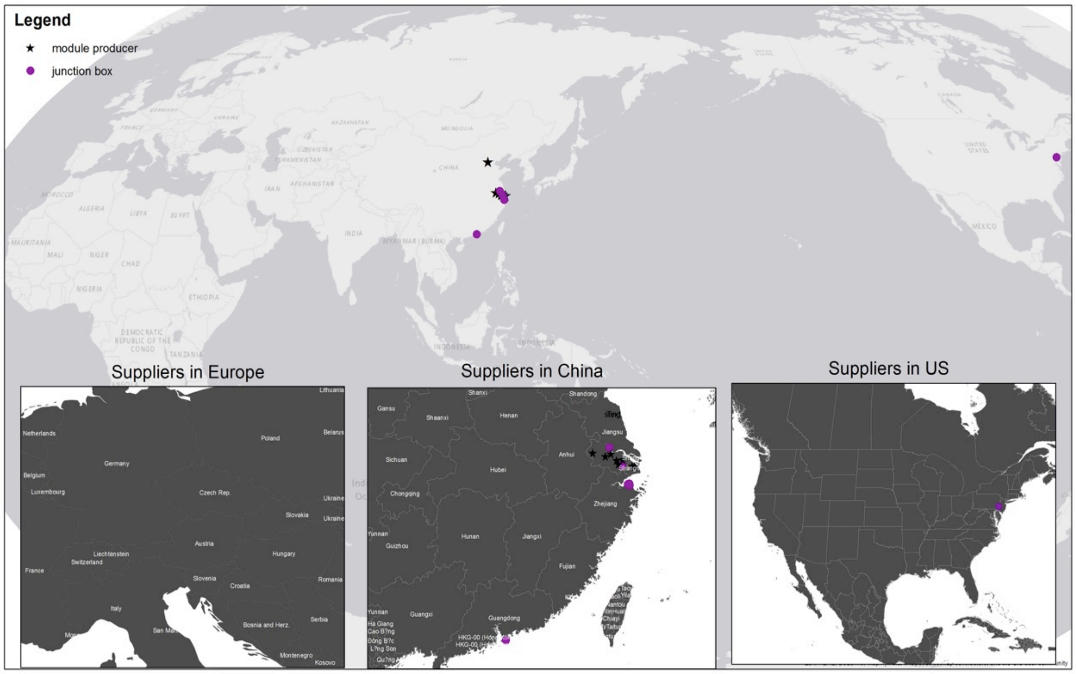

Figure D. 2. Global Top 10 PV Junction Box Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

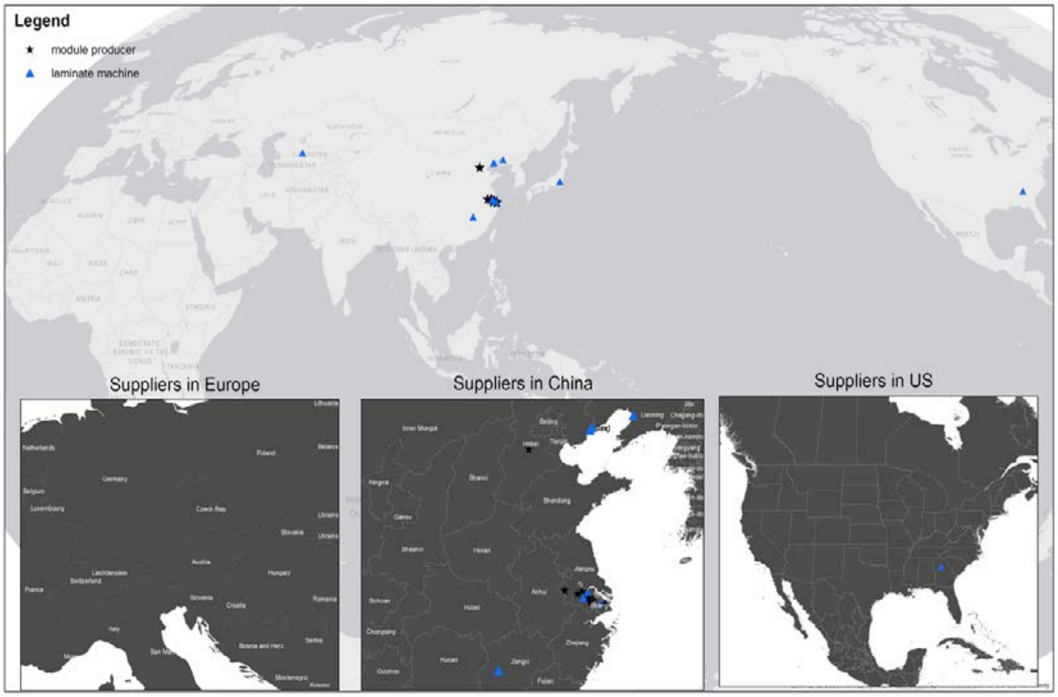

Figure D. 3. Global Top 10 PV Laminate Machine Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

Weaknesses of China's supply chain that are improving

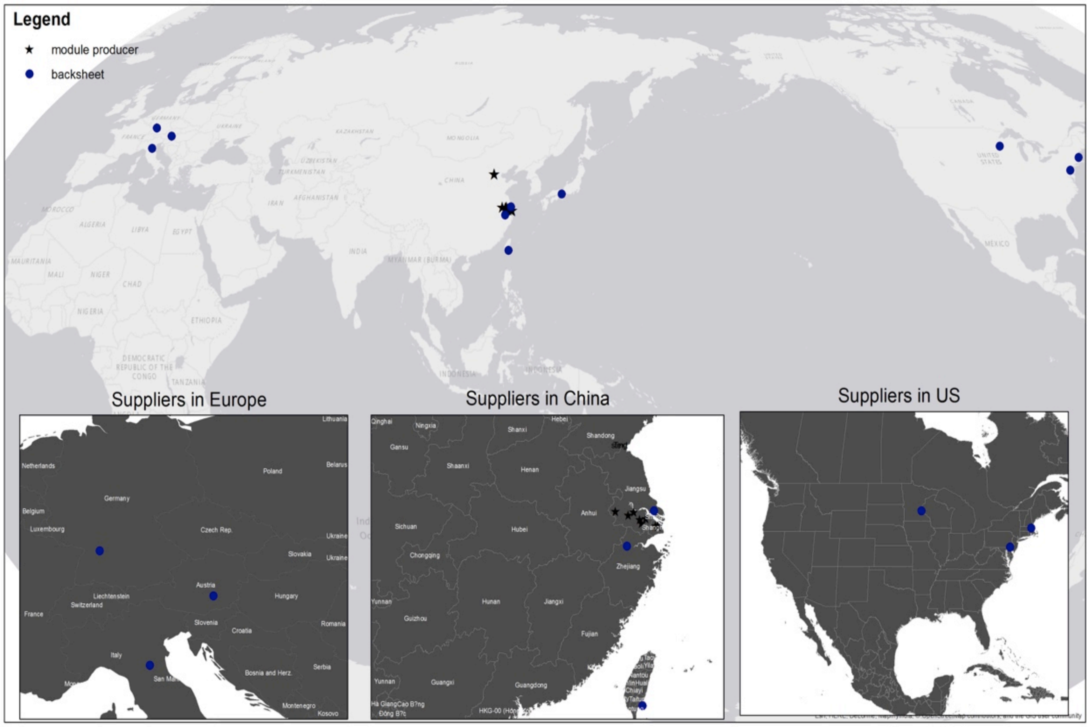

Figure D. 4. Global Top 10 PV Back Sheet Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

Figure D. 5. Global Top 10 PV EVA Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

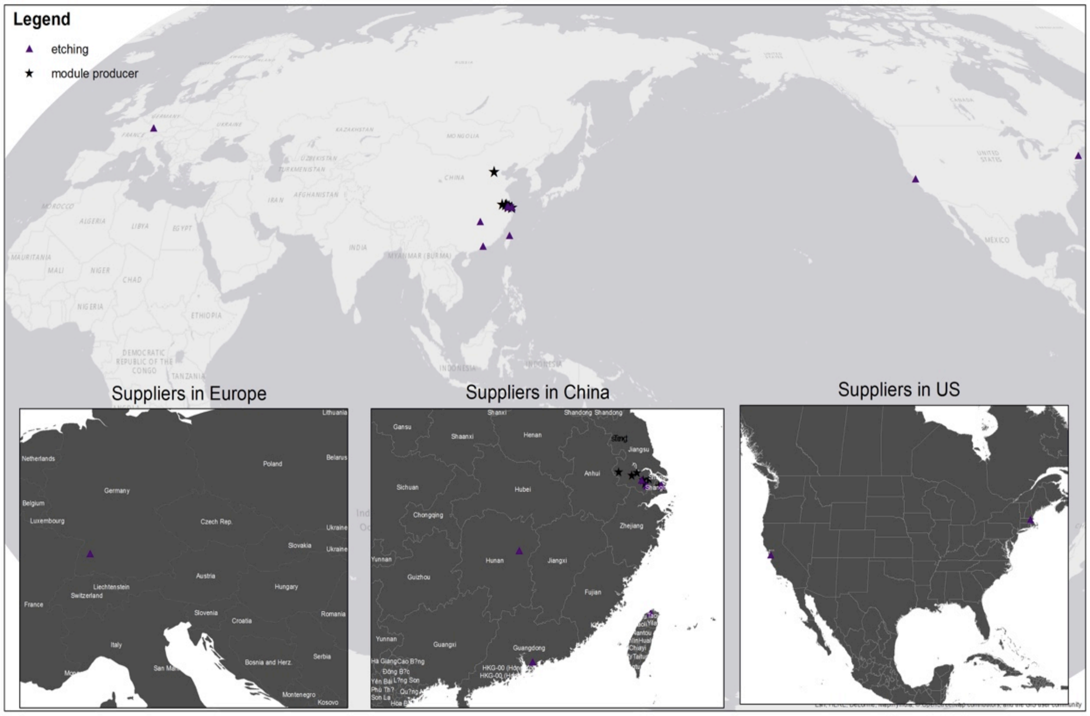

Figure D. 6. Global Top 10 PV Etching Machine Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

Weaknesses of China's supply chain that are stagnant

Figure D. 7. Global Top 10 PV Silver Paste Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

Figure D. 8. Global Top 10 PV String Machine Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

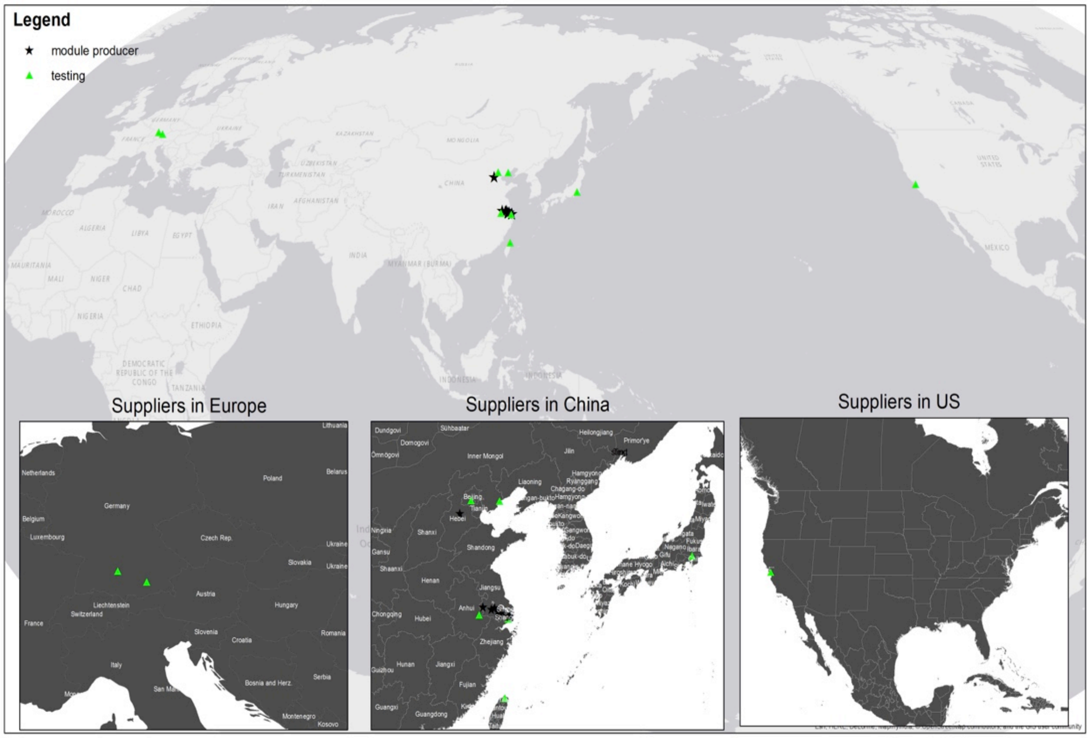

Figure D. 9. Global Top 10 PV Flash Test Machine Suppliers in 2013

Sources: ENF Chinese Cell and Panel Manufacturers Survey the Continuous Edition Analysis Report.
Note:
The subscription to the ENF database came through the Stanford China Project.
The map was created as part of the Stanford China Project by the author of this dissertation, Cait Pollock and Jingfan Wang, all members of the Stanford China Project research team.

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